Alpha-SIM

A quick 3D geometry model simplification approach to support aircraft EWIS routing

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α-SIM: A 3D geometry model simplification and idealization approach using 2D α-Shape

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Abstract

Digital MockUps (DMUs) represented by CAD data are widely used in engineering practices. It has been noticed that in a collaborative design process (e.g., path routing of cables or pipes for a vehicle), DMUs obtained from upstream partners may include over-detailed features, such as screw threads and gear tooth. These features hardly influence the results of current design but significantly increase rendering and computational time and cannot be easily suppressed since the DMUs are commonly stored in neutral formats (e.g., STEP or IGES) and the information of features does not exist any more.

Aimed at simplifying the CAD models to facilitate downstream applications, a geometric simplification and idealization method named α-SIM is presented. This method is inspired by Descriptive Geometry techniques and 3D modelling approach using 2D sketches. Descriptive Geometry techniques can obtain 2D profiles that include the main features of the CAD model and 3D modelling is able to rebuild a 3D model from the 2D profiles/sketches. This method cares more about the intuitive notional shape of the CAD model rather than its low level primitives, such as vertices, edges, and faces. The intuitive notional shape is represented by a set of 3D cloud points and their 2D projections on coordinate planes. The 2D profiles are α-Shapes of each 2D point sets. Via controlling the density of the 3D cloud points and the α value, various geometric approximations will be achieved. The results of engineering test cases demonstrate promising prospects of this method in geometry simplification and idealization applications.

Keywords: Geometry simplification, 2D alpha-shape, CAD

1. Introduction

Digital MockUps (DMUs) represented by CAD data format are widely used in modern engineering practices, such as modelling, analysis, and simulation. Nevertheless the quality of some CAD models are not satisfactory. A complex system will be systematically decomposed into some sub-systems. These sub-systems are designed collaboratively and/or iteratively at various participants. A set of DMUs is a pivotal output of each sub-system. In each design loop, the upstream DMUs are required to carry out the design of current sub-system. It has been noticed that the DMUs received from upstream suppliers sometimes are over-detailed to current design. For instance, designers of aircraft Electrical Wiring Interconnection Systems (EWIS) receive DMUs of aircraft and equipment from aircraft designer and other equipment suppliers to determine where they can put clamps and route wire harnesses; where geometry obstacles they need to avoid are; where receptacles that harnesses need to connect with are; and so forth. Sometimes the DMUs they get are already mature enough for manufacturing and include many over-detailed geometric features for cable wiring, such as chamfers, slots, rivet holes, and screw thread (see Figure 1). These features hardly influence the results of current design but significantly increase the model size as well as the time of geometry rendering

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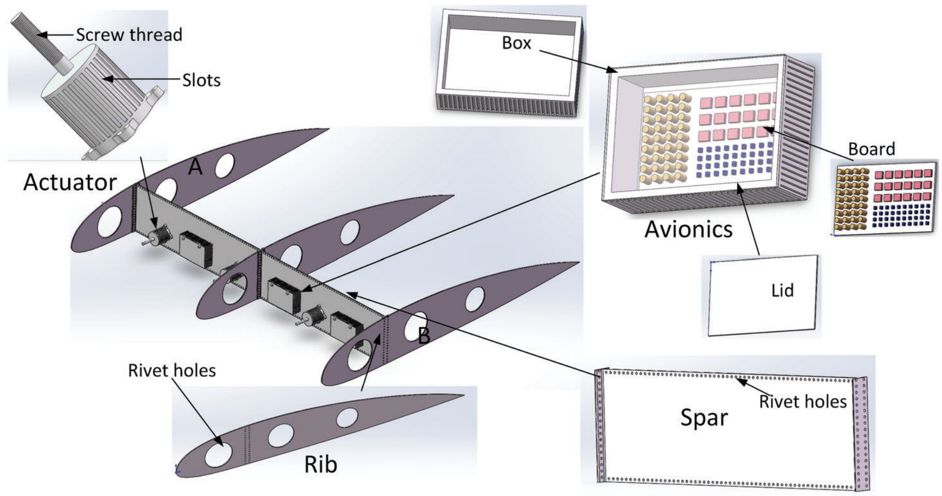

Figure 1: Illustration of an EWIS routing environment

and computing, such as collision check. Similar problems are faced by the designers of hydraulic/fuel pipes and air duct for aircraft as well as the designers of pipes and cables for ship and offshore plants [1].

In industry, the designers already take actions to handle the over-detailed equipment, such as 1. generating simplified 3D CAD models manually; 2. hiding some of the CAD models; 3. mentally ignoring some of the CAD models; and 4. using triangulated format(e.g., Catia CGR) to represent the actual CAD model. Nevertheless, the manual work does not suitable for current collaborative design process which generally consists of many design iterations. The problems of the rest solutions are also noticed by EWIS engineers during their daily work and are presented in [2].

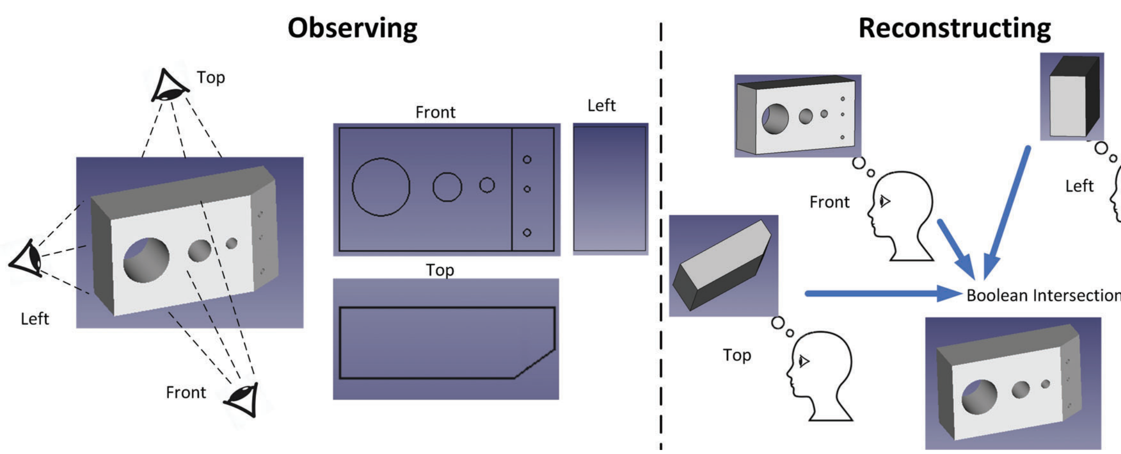

Figure 2: Illustration of an observation and reconstruction process of a 3D model

Therefore, a geometry simplification and idealization approach that is able to get rid of unnecessary geometric features of CAD models is needed. The method needs to be time efficient since the upstream DUMs, namely the routing environment, will be updated many times in the above mentioned iterative engineering practices. The EWIS designers also prefer to control the LODs (Level of Details) of simplification results (e.g., rough or fine approximations) via adjusting some parameters to satisfy different application scenarios.

Considering the two requirements, we proposed a novel simplification method, called α-SIM (**S**implification and **I**dealization **M**ethod using 2D **α**-shape), in this paper. Instead of diving into mesh or low primitives (i.e., vertices, edges, and facets) of an actual CAD model, α-SIM cares more about the outer 2D profiles of the model. This method is inspired by the Descriptive Geometry technique and the 3D CAD modelling process. When using descriptive geometry technique, a 3D CAD model can be projected onto several 2D planes to form 2D drawings. The reader is able to reconstruct the 3D CAD model from the 2D drawings in their mind. In 3D CAD modelling, a 3D model is generated from 2D sketches using various methods, such as *Extrude*. As shown in Figure 2, a geometry may contains multiple features (e.g., holes and fillet) and projecting to and extruding from one 2D plane is not sufficient to represent all these features. Hence, multiple 3D models need to be generated to represent a part of the features respectively. Finally, a Boolean intersection needs to be carried out to generate a single 3D model which includes all the features. Therefore, a 3D CAD model is reconstructed.

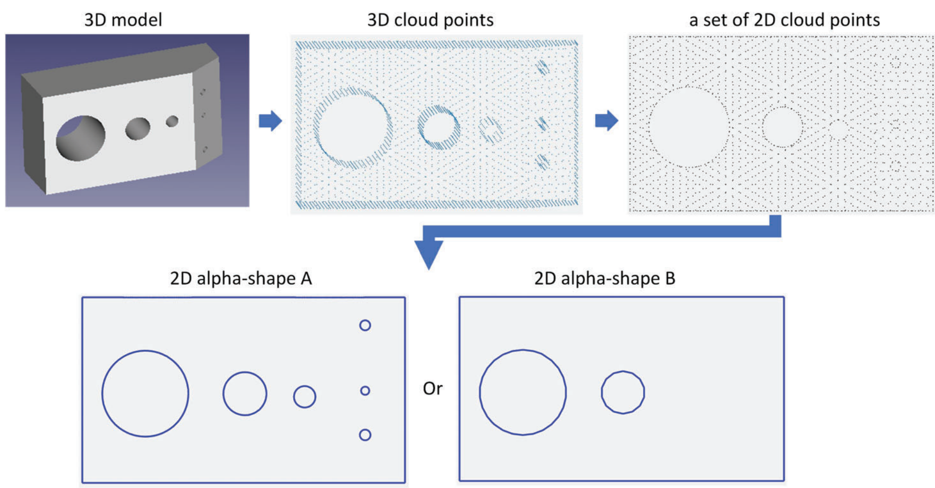

Figure 3: Process of 3D model sampling and 2D shape reconstruction

Nevertheless, the LODs of simplification results cannot be adjusted yet in this process. In order to achieve this function, a 3D shape sample and 2D shape reconstruction approach is applied when generating 2D sketches from the 3D CAD model. As shown in Figure 3, the 3D model is first tessellated into a set of 3D cloud points. Then, the set of 3D points will be projected onto 2D planes to form 2D intuitive notional shapes (in Figure 3, only one 2D points projection is presented as an example). Next, an α-Shape of the set of 2D points can be generated. During generating α-Shapes, different 2D approximations can be achieved when selecting proper α values, such as α-Shape A and α-Shape B in this picture. In α-Shape B some small holes are removed for a bigger α value is used. Therefore, different approximations of the 3D CAD model will be finally achieved. The relationship between the simplification level and the α value will be detailed in Section 3.

In the remainder of this paper, related geometry simplification and shape reconstruction work is first discussed in Section 2. In Section 3, the development of the α-SIM is presented. Then the key techniques of the method are detailed. Some test cases are presented in Section 4 followed by conclusions and recommendations in Section 5.

2. Related work

2.1. Review of geometry simplification methods

The necessity of simplification and idealization of CAD models have already been noticed and diverse simplification and idealization approaches have been studied. These methods can be classified into 1) mesh simplification, 2) geometric feature-based simplification, and 3) boundary representation (B-rep) model simplification.

One type of mesh simplification methods focus on reducing the number of vertices, edges, facets, and cells via incrementally deleting and merging the adjacent elements to decrease the complexity of the original model [3, 4, 5]. The other type of the method recognizes features from a mesh model and then remove all the triangles enclosed by the features to simplify the mesh[6, 7]. The geometric feature-based simplification suppresses the less important features stored in the product tree according to some metrics to achieve a simple CAD model.[1, 8]

In the engineering practices considered in this paper, the target CAD models are defined using B-rep method and stored in neutral CAD file exchange formats (STEP and IGES) for the compatibility with other partners and the protection of intellectual property. The mesh as well as the features tree and information of modelling sequence are not included in the file. Therefore, the first two simplification methods are not applicable here.

The third one, namely B-rep model simplification, includes dimensional reduction method as well as Feature Recognition and Suppression Method(FRSM). The former transforms the 3D representation into 2D and 1D (e.g., faces and edges)[9, 10] and the latter first recognizes the features from B-rep models and then suppresses the less important ones according to evaluation metrics [11, 12, 13]. The result of dimensional reduction is more suitable for CAE analyses, but it is not able to represent the space occupancy of the equipment in a very crowded routing environment. The geometry collision-free cable routing results(e.g., pipe and cable) in the simplified routing environment may collide with the actual 3D CAD models. The FRSM is a promising solution for the geometry simplification application in this paper. Many feature recognition research works can be found in a review paper[14]. Nevertheless, as indicated in the paper that "the complete problem (of feature recognition) is far from being resolved". B. C. Kim and D. Mun also point out "..., B-rep simplification can be applied to only limited shapes, and the control of the LOD is not easy."[15] Indeed, similar problems are noticed in our daily work. First, not all features can be recognized and therefore can not be suppressed. Some features, such as holes, chamfers, fillets can be easily recognized, but other features, such as the screw thread in Figure 12, are very difficult to be recognized (if it is not impossible). Second, this method may be capable but not suitable for low Level of Details(LODs) simplification due to the its efficiency. This method first needs to carry out a very time consuming feature recognition process. Then it suppresses the less important features, provided the features can be successfully recognized. The simpler the simplification result is, the more time is needed. In a cable or pipe routing practice, a designer may only be interested in the outer profile of a CAD model. The profile can be the shape of main features, convex hull, or even bounding box. Achieving such low LOD simplification results using the FRSM is too time consuming. On the other hand, the information represented by bounding box or convex hull may be not adequate for the engineering practices.

Therefore, as mentioned in Section 1, a novel simplification method, α-SIM, is proposed. One of the criteria to evaluate the performance of a geometry simplification method is whether the features intended to be suppressed are removed and the features intended to be preserved are kept. From this perspective, the performance of α-SIM is significantly influenced by the effect of the 2D shape reconstruction.

2.2. Review of 2D shape reconstruction methods

Given a finite set of planar points $S \subseteq \mathbb{R}^2$, shape reconstruction tries to generate a set of polyline connecting a points set $S^* \subseteq S$ to express the intuitive notional shape of S, such as the two α-Shapes shown in Figure 3.

Shape reconstruction is a very challenging and crucial problem in several domains and is extensively studied. A very early attempt to recognize the intuitive notion of a point set is α-Shape[16]. α-Shape is the space generated by connecting all point pairs that can be touched by an empty circle of radius $1/\alpha$. α is a variable. If α equals 0, the output is a convex hull of S. Via choosing a proper α value, both the outer boundary and inner boundaries (holes) can be reconstructed. The effect and efficiency of this method is significantly determined by the density of points S. A uniform distribution of S will improve its effect and efficiency. When the points in S is not uniform or too sparse, expected α-Shape may not be able to be generated to represent the shape of S. In order to take care of this issue, A-Shape [17] is proposed. This algorithm first adds a finite set of auxiliary points A to S and then constructs Delaunay Triangulation (DT) of $S \cup A$. Finally, a pair of adjacent points in S will be connected if and only if they are two endpoints of an edge in a Delaunay triangle. Another DT based parametric shape recognition method is known as χ-Shape[18]. This algorithm removes the external longest edge in the DT until the longest edge on the boundary is less than a threshold value L. The efficiency and termination condition of this algorithm is affected by the threshold value. By selecting a small value for L, more details on the shape can be obtained. However this method is only able to generate the outer boundary of a point set S, inner boundaries(i.e., holes) cannot be reconstructed. Another outer boundary recognition algorithm, simple-Shape[19], starts reconstruction from the convex hull of a point set S and makes the outer shape concave step by step. This algorithm works for both BS (Boundary Sample) and DP(Dot Pattern) but is also not able to detect inner boundaries.

In the above mentioned methods, parameters need to be tuned in order to obtain the expected shape. Therefore, such methods are classified into parametric shape reconstruction approaches. On the contrary, the approaches presented below are known as non-parametric method. Crust[20] and NN-crust[21] are algorithms designed to reconstruct outer and inner boundary (curves for 2D and surfaces for 3D) from a 2D/3D point set S. RGG(Relaxed Gabriel Graph)[22] is designed to detect the outer boundary of sample points. It is also able to recognize the inner boundary provided the points set on the inner boundary edge forms a fat triangle and some thin triangles and the fat one is surrounded by the thin ones. Recently, an Empty Disk Approach[23, 24] is proposed. This algorithm is able to reconstruct outer and inner boundaries for both BS and DP. Nevertheless, the LODs of the output shape cannot be adjusted by end users when using this method.

In the simplification application considered in this paper, both outer and inner boundary of cloud points need to be detected and the LOD of the simplification needs to be adjusted by the end user to satisfy the requirements at different design phases. Therefore, the non-parametric methods and the methods that cannot reconstruct the inner boundaries are excluded. α-Shape method becomes the best candidate for the shape reconstruction. Although the performance of this method largely depends on the density and uniformity of the sample points, the sample points are generated via tessellating the CAD model about to be simplified and the end user has a full control of the tessellation process. Therefore, the drawbacks of the α-Shape will be avoid in this application.

3. Development of the simplification and idealization method(α-SIM)

In this section, the workflow of α-SIM is presented first. Then, the key techniques that influence the effect and efficiency of the method are discussed.

3.1. *Workflow of α-SIM*

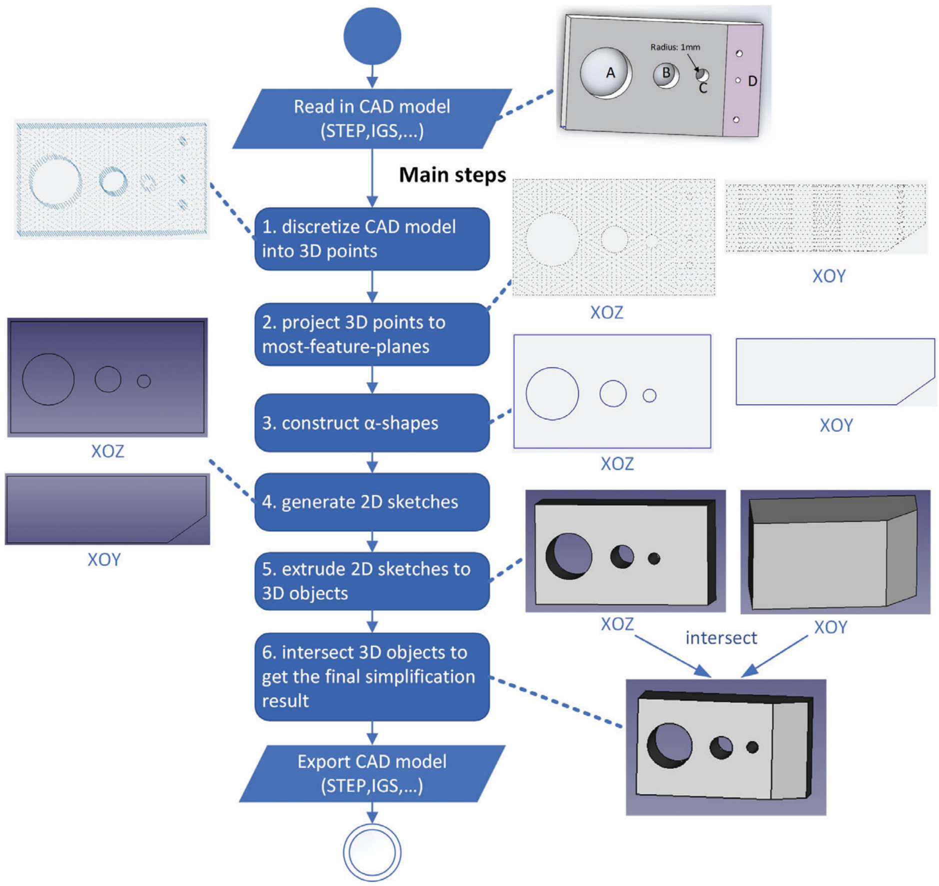

Figure 4: Workflow of the simplification and idealization method(α-SIM)

The α-SIM is designed to simplify a component (part). If the input geometry is an assembly, the simplification can be carried out per its component or the assembly first compounds into one part if the assembly is considered as a component [1]. The method consists of 6 main steps, which are illustrated in Figure 4) and introduced below:

1). discretize CAD model into 3D points: after reading in a CAD model, the α-SIM first discretizes the model into 3D cloud points, which represents the intuitive notional shape of the actual CAD model, via surface triangle tessellation. The 3D points are the all vertices of triangles. This tessellation can be done by mainstream geometry kernels, such as Open Cascade used here. The default tessellation method will generate as less triangles as possible to represent a surface. In this discretization process, the only parameter that needs to be controlled is the maximum allowed tessellation size $L_{max}^{allowed}$ (i.e. the maximum allowed distance between adjacent points) since it will determine the density of cloud points and the density of the points influence the effect and efficiency of generating α-Shapes. Denser cloud points increases the generation time of a α-Shape but too sparse points may lead to failure to generate an expected α-Shape. The method to select a proper $L_{max}^{allowed}$ will be detailed in the next Subsection. Here pictures in Figure 5 illustrate the relationship between $L_{max}^{allowed}$ and tessellation result;

[1]For instance, a device is an assembly. When the device is placed in a wing, it is considered as single part since the assembly relationship in the device is not interesting for harness designers. Hence, the device is first compounded together and simplified as a component.

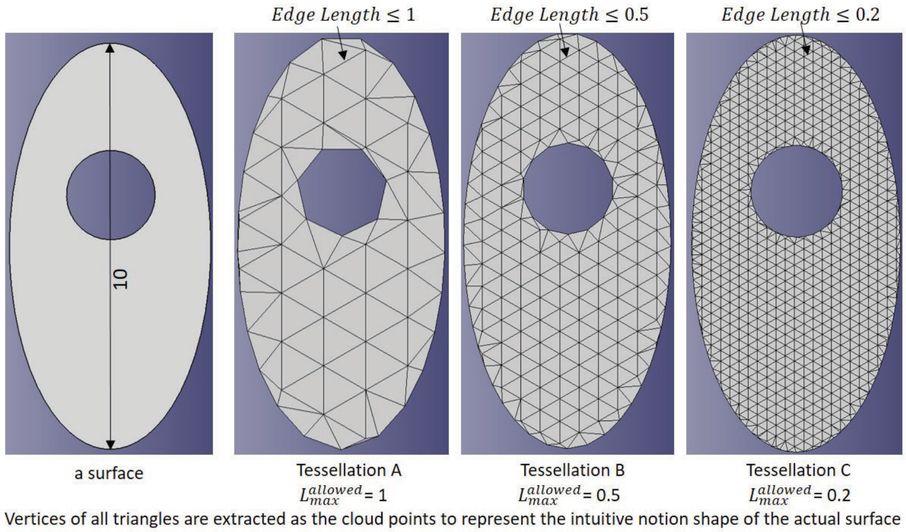

Figure 5: Tessellation results of a surface with different $L_{max}^{allowed}$

2). project 3D points to the most-feature-planes: when using the descriptive geometry techniques, a 3D CAD model can be described by pictures on some 2D planes, such as XOY, XOZ, and YOZ planes of Cartesian coordinates. Projection of the CAD model on these planes preserves the most features of the model. These 2D planes here are call most-feature-planes. In practice, not all Cartesian coordinate planes need to be selected for projecting. In the example illustrated in Figure 4, XOY, XOZ planes are adequate since projection on these planes already includes all the features, namely: the holes, fillet, and the 3D dimensions of the slab. On the other hand, the three Cartesian coordinates planes sometimes may not be enough for a complex CAD model. In this case some auxiliary planes need to be defined by the end user. Currently, the XOY, XOZ, and YOZ planes are considered as the default most-features-planes for the automation of the simplification process. Users are also permitted to delete the planes from or add auxiliary planes to the most-feature-planes list when they think it is necessary. Then 3D points will be projected to these planes to generate some 2D point sets;

3). construct α-Shapes: α-Shapes will be constructed from each 2D point set. They are used for generating sketches to rebuild the simplified CAD model. Small features can be eliminated via controlling the α value therefore different geometric approximations are achieved. According to Edelsbrunner et al. [1983], "*the α-Shape is the intersection of all closed discs with radius l/α that contain all the points of S*" if α is positive real; "*the α-Shape is defined as the intersection of all closed* ***complements*** *of discs (where these discs have radii - l/α) that contain all the points of S*" if α is negative real.[16] In practice, the negative α-Shape is more widely used since it is more flexible and can reconstruct holes from a points set. Gradually, the definition of α-Shape has been evolved in later research works [25, 26]. Below, the definition of 2D α-Shape used in this paper is given:

Definition of 2D α-Shape : the 2D α-Shape is the boundary of $Tri = \{t : r_t < \alpha, t \in DT(S)\}$, where DT($S$) is a Delaunay triangulation for a given point set S in a plane such that no point in S is inside the circumcircle of any triangle in DT(S); t is a triangle in $DT(S)$. r_t is the radius of the circumcircle of t; α is a non-negative real number.

α-Shape is a convex polygon if α is approaching infinite or sufficiently big and α-Shape is empty if α is sufficiently small. Via adjusting α value, different approximations can be achieved (see Figure 6). In this figure, $DT(S)$ is generated first from the point set S. Then the triangles whose circumradius are smaller than α are removed from $DT(S)$ to generate $Tri \subseteq DT(S)$. The Tri sets obtained using different α values represent different intuitive notions of the original point set. Finally, edges of Tri that are not shared by more than two triangles are connected to form the outer and inner boundary of the α-Shape.

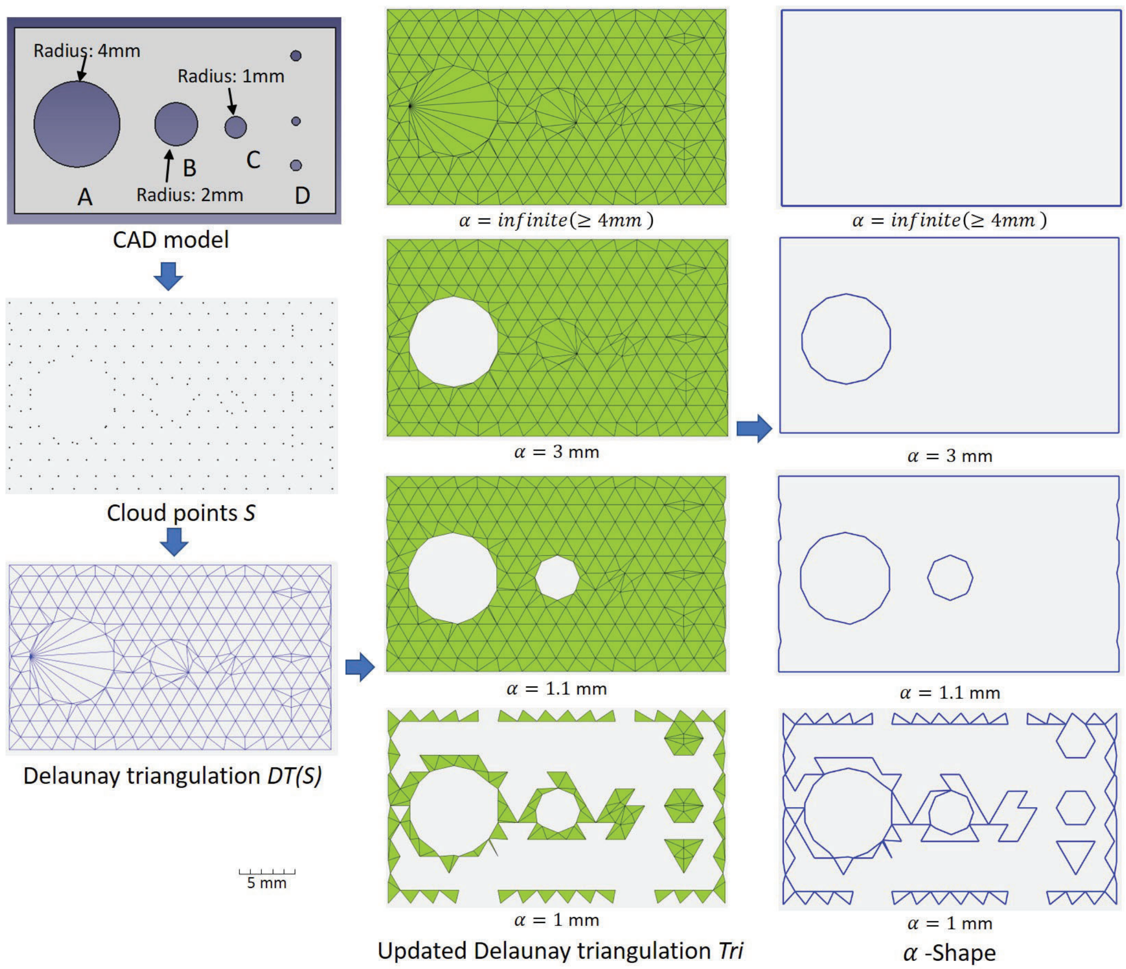

Figure 6: Diverse approximations of the point set S via using different α value

4). generate 2D sketches: an α-Shape of a set of points is polyline but a 2D sketch normally is a combination of line segments and/or curves. Therefore the piecewise line segment chains of the polyline which are collinear (i.e., included angle of adjacent line segment is smaller than 1×10^{-6} deg) are transformed to line segments. The rest line segment chains (i.e., the ends of line segments) are transformed into curves via a spline interpolation;

5). extrude 2D sketches to 3D models: extruding 2D sketches with the dimensions of the actual CAD model generates 3D CAD models and each 3D model contains the features that are visible from the perspective perpendicular to its sketch. For instance, extruding the 2D sketch on XOZ plane along axis Y at distance equal to the width(along Y) of the actual CAD model generates a 3D model. The model contains the features that are visible when observing the model along Y axis. The features that are intended to be removed (e.g., small holes) do not exist any more;

6). intersect the 3D models to get the final simplification result: each 3D model obtained via previous step contains a part of the features of the original model. In order to obtain a single 3D CAD model preserving all the features, the 3D models intersect with each other. As shown in Figure 4, the holes (i.e., features on XOZ extrusion) and fillet(i.e., features on XOY extrusion) are all preserved in the final simplification result.

Finally, the simplified result will be exported in a neutral CAD format, which is the same as the input file, to replace the actual CAD model.

3.2. Discussing the parameters influencing the effect and efficiency of α-SIM

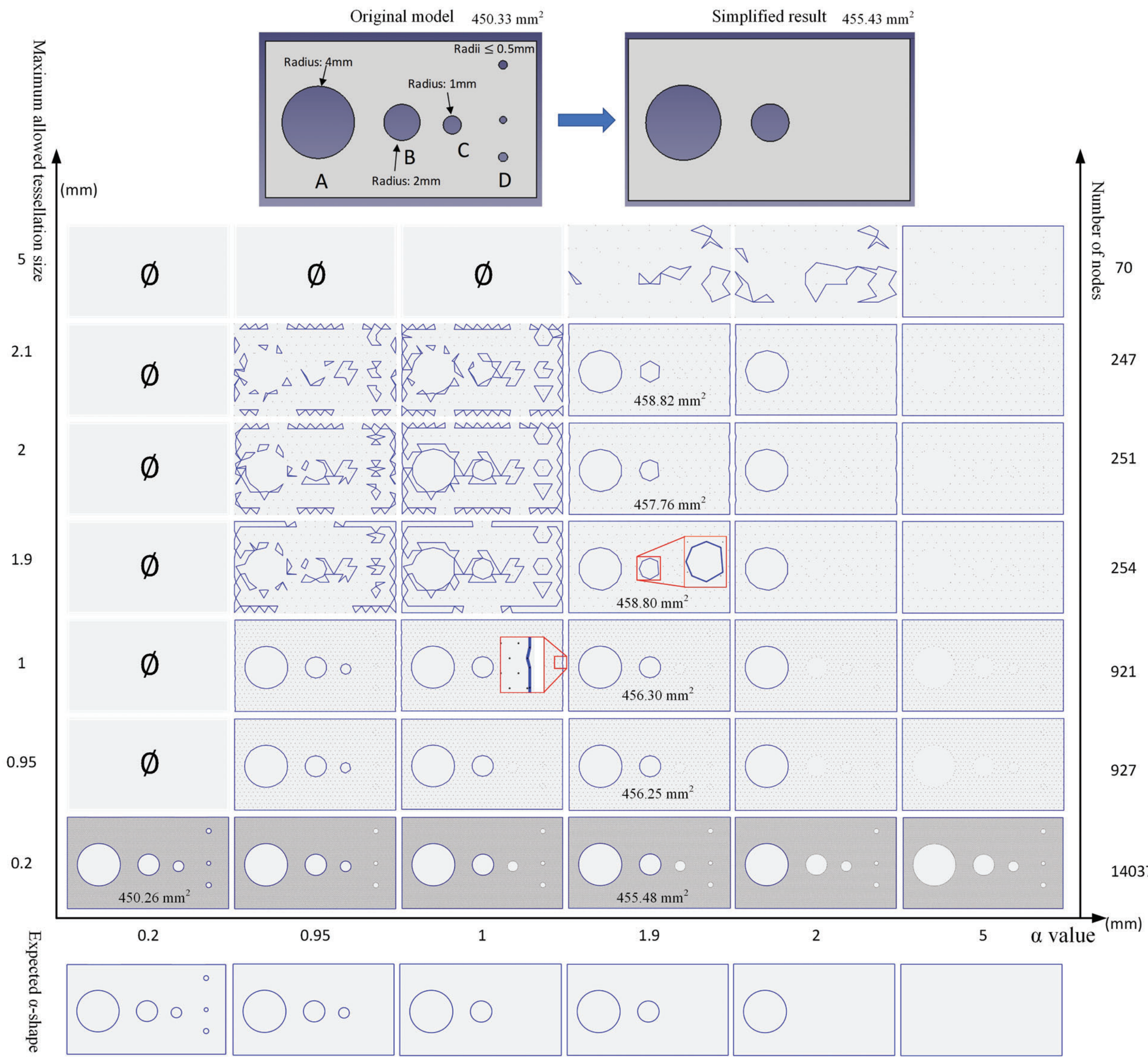

Figure 7: Influence of the maximum tessellation size and α value on the effect and efficiency of the geometry simplification

The effect and efficiency of α-SIM largely depends on whether the expected α-Shape can be reconstructed from the points set and the efficiency of the reconstruction process. A successful and efficient shape reconstruction is determined by an appropriate α value and an appropriate density of the cloud points, namely the maximum allowed tessellation size $L_{max}^{allowed}$. For instance, the cloud points in Figure 6 are too dense (i.e.,low efficiency) if only the outer profile or the Circle A needs to be reconstructed. This will increase the time on the α shape reconstruction. On the other hand, the points are too sparse (i.e., unsuccessful reconstruction) if Circle C needs to be reconstructed. The profile of Circle C can not be recognized from the point set.

In this Subsection, a tessellation and shape reconstruction example is given in Figure 7 to illustrate the influence of $L_{max}^{allowed}$ and α value on the effect and efficiency of the geometry simplification. In this simplification example, the features whose dimension [2] are equal to or smaller than $1mm$ are expected to be suppressed and features whose dimension are equal to or lager than $2mm$ are intended to be preserved.

Here, 7 set of cloud points, whose points number vary from 14037 to 70, are generated with $L_{max}^{allowed}$ varying from $0.2mm$ to $5mm$. The smaller $L_{max}^{allowed}$, the more points are generated. Then the α-Shapes for each points set are generated with α value varying from $0.2mm$ to $5mm$, as shown in Figure 7. From this figure, the following states are noticed:

- A sufficiently small $L_{max}^{allowed}$ and α (i.e., 0.2 mm) enables an accurate shape reconstruction. Here, the accuracy is evaluated by the area of the expected CAD model S_{exp} and the α-Shape S^{α}. It is defined as $\frac{|S_{exp}-S^{\alpha}|}{S_{exp}}$. According to this definition, error of the α-Shape $\{L_{max} = 0.2 \cup \alpha = 0.2\}$ is 0.015%. A more accurate approximation can be expected if a further smaller $L_{max}^{allowed}$ is adopted.
- α value controls the LOD of the simplification result. The features whose dimension is smaller than or equal to α are suppressed and the features whose dimension is larger than α are preserved. The α should be smaller than but as close as possible to dim_{pre}. Otherwise the non-smooth edge in $\{L_{max} = 1 \cup \alpha = 1\}$, which should be a straight line segment, may occur.
- Given an α value, too large $L_{max}^{allowed}$ will lead to an empty or ill conditioned α-Shape, whose error is 100% or more than 50% respectively. Provided the α can be generated, the accuracy of the simplification result is largely determined by the $L_{max}^{allowed}$. Although an α-Shape can be generated when the $L_{max}^{allowed}$ (approximately) equals to α, the shape is not satisfactory, such as the non-smooth edge in $\{L_{max} = 1 \cup \alpha = 1\}$ and the irregular polygon in $\{L_{max} = 1.9 \cup \alpha = 1.9\}$. It is noticed that an satisfactory simplification result can be achieved when $L_{max}^{allowed}$ is smaller than half of α, namely half of dim_{pre}.
- When a α-Shape is already satisfactory(e.g., $\{L_{max} = 1 \cup \alpha = 1.9\}$), decreasing $L_{max}^{allowed}$ further will negligibly increase the accuracy of the approximation, such as 0.18% for decreasing $L_{max}^{allowed}$ from $1mm$ to $0.2mm$ (i.e., from $\{L_{max} = 1 \cup \alpha = 1.9\}$ to $\{L_{max} = 0.2 \cup \alpha = 1.9\}$) . Nevertheless, the computing time will increase significantly. Most computing time of α-SIM is consumed on tessellation and Delaunay triangulation for generating α-Shape. The time complexity of Delaunay triangulation is $O(nlogn)$ and of tessellation will not be better than $O(nlogn)$. It is a reasonable assumption that the time complexity of α-SIM is $O(nlogn)$. In this case, the time consumed on α-Shape reconstruction at $L_{max} = 0.2mm$ is 21.3 times more than at $L_{max} = 1mm$. This cost is too high for only a 0.18% increase on the accuracy.

According to the previous states, the maximum allowed tessellation size $L_{max}^{allowed}$ is set to 50% of dim_{pre} to maximize the efficiency without compromising accuracy of the shape recognition. α equals 95% of dim_{pre} so that an expected α shape can be constructed. The values of both α and $L_{max}^{allowed}$ will be changed if dim_{pre} is adjusted so that various approximations will be achieved.

4. Applications of the simplification method and results

In this section, 4 test cases are carried out.

The method is applied to the simplification of both components and an assembly model, which is a harness routing environment. A comparison between α-SIM and Feature Recognition and Suppression Method is also presented.

4.1. Geometry simplification of an aircraft wing section for 3D harness routing

The DMU in Figure 1 is a representative routing environment. It includes structures (i.e., ribs and spars), actuators and avionics. A harness will be routed from point A to point B in front of structures. 6 branches will be broken out from the harness to connect with the 6 receptacles on the 3 avionics.

[2] Dimension of a feature is defined as the radius of its circumscribed circle(2D) or sphere(3D).

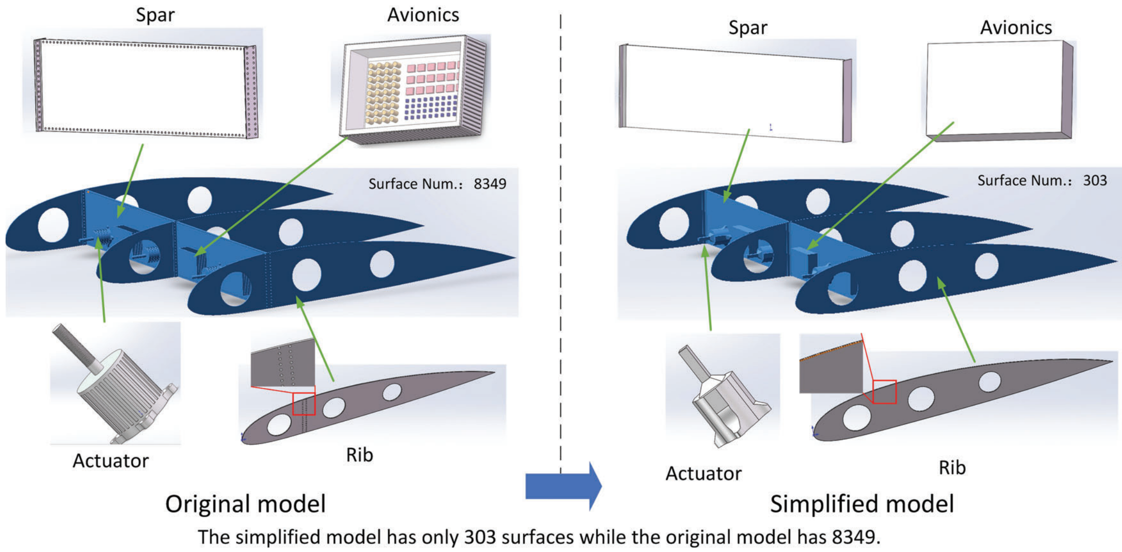

Figure 8: Simplification result of an aircraft wing section

As shown in Figure 1, this DUM contains many irrelevant features to harness routing, such as rivet holes on ribs and spars; the slots and screw thread on actuators; the slots and the interior board of avionics. These features will be removed using the α-SIM. The receptacles, whose location, direction, and dimension will be used for harness routing will be kept as is. This DMU is an assembly model. The sub-models it contains include components (e.g., ribs and a spars) and assembly models (e.g., avionics boxes). The simplification of this DMU is carried per sub-model, no matter whether the sub-model is a component or an assembly. If a sub-model is an assembly, the components of this sub-model is first compounded into a new component, then the rest of its simplification process is the same as a component model. When the simplification of all sub-model is finished, the simplified results are combined to generate the simplified DMU. Since the actual position and dimension of sub-models are used in the simplification process, the simplified sub-models still occupy the same position as the original ones but are much more concise. In this example, the surface number of the simplified DUM is only 3.6% of the actual DMU (303 and 8349 respectively). The simplification result is illustrated in Figure 8.

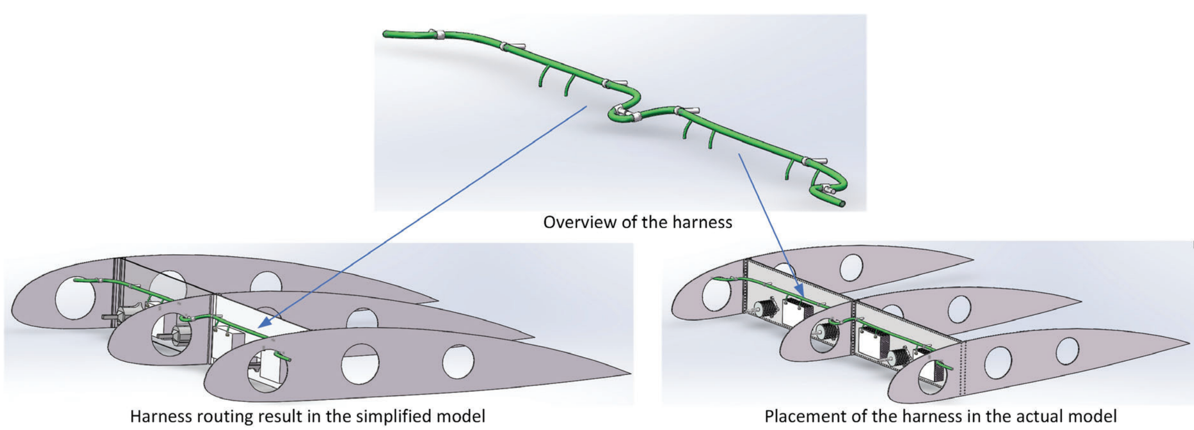

Figure 9: Harness routing result in an aircraft wing section. Bottom left: Harness in the simplified model; Top: Independent view of the harness; Bottom right: Harness in the actual geometry model

Then, the engineers can route harnesses in the new routing environment. When the routing is finished, the routing results are already mature enough for manufacturing and guiding installation. If necessary, the actual DMU can be loaded into the routing system to replace the simplified one for a final check. The satisfactory routing results in the simplified routing environment will not bring new violations (e.g., geometry collision) in the actual DMU. The routing result in the simplified and actual DMU as well as the harness itself are illustrated in Figure 9.

4.2. Geometry simplification of an actuator with different LODs

The previous example demonstrates the simplification of an assembly model. In order to show the relationship between LODs of the simplification results and the values of parameters, the simplification of a component with 3 sets of parameters is given in this test case.

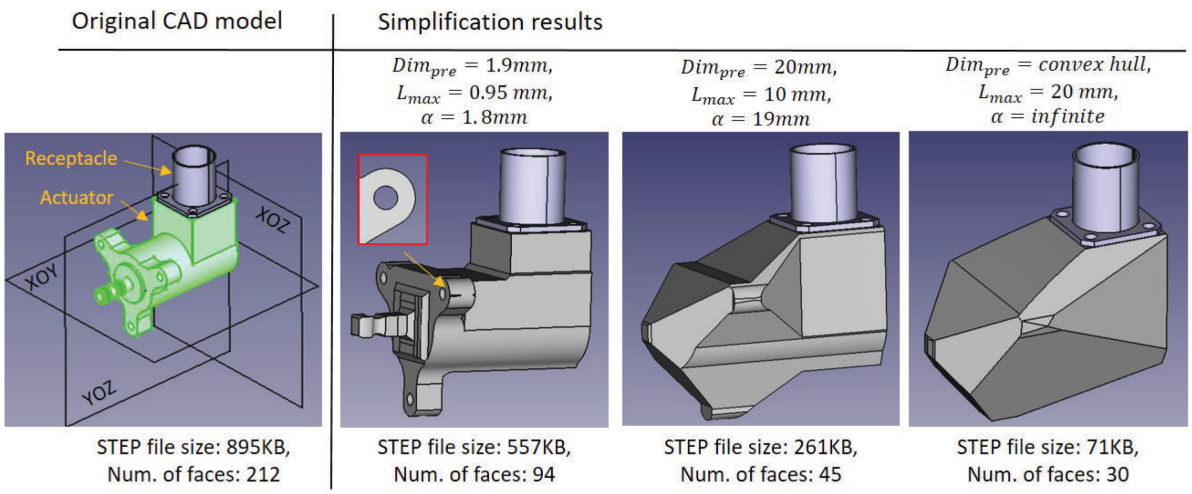

Figure 10: Simplification of an actuator with different approximations(i.e., different α values)

As shown in Figure 10, the model stored in STEP file consists of a receptacle and an actuator. These two models can be recognized from their name. The actuator is going to be simplified and the receptacle will be kept as is. Three sets of L_max and α are adopted for three different geometry approximations. XOY, XOZ, and YOZ planes are selected as the default most-feature-planes. Within each set of parameters, the 3D cloud points are projected to these planes and the α-Shapes are constructed on each plane respectively. Then three 3D models are built from the α-Shapes using extrusion. Each model contains a part of features of the actual model. Finally, these three models are intersected with each other to generate a simplified CAD model. The simplification results of all three parameter sets are presented in Figure 10.

The bigger Dim_{pre} is, the more features will be removed. As the consequence, the LOD of simplification models decreases when the value of Dim_{pre} increases. On the other hand, the model is much more concise. In this example, when most features are removed, the STEP file size and faces number of the simplified model are decreased to only 7.9% and 14.2% of the actual model respectively. Via selecting proper parameters, the end users can obtain their expected simplification level.

4.3. Geometry simplification of a helical gear

α-SIM takes advantage of the outer profiles rather than manipulates very detailed features of a CAD model. When only the profiles are required to be preserved in the target model, it is more efficient while comparing with other conventional simplification methods, such as Feature Recognition and Suppression Method(FRSM).

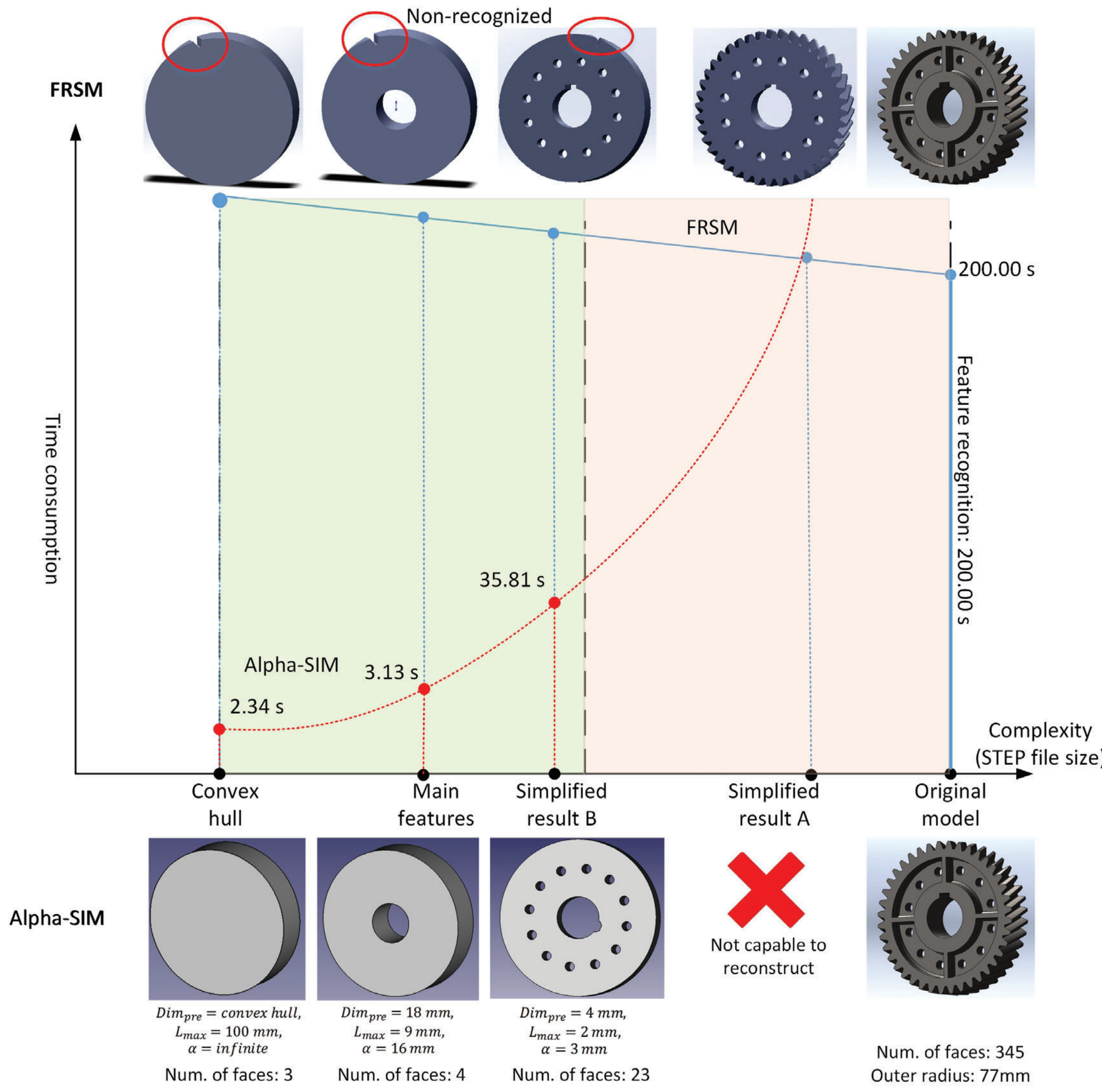

Figure 11: Comprising the performance of α-SIM and Feature Recognition and Suppression Method

In this test case, a helical gear, as shown in Figure 11, is simplified using both α-SIM and FRSM. Various LOD results are generated. The time consumption and the effect of both methods at different LODs are discussed.

The α-SIM of this example is performed with different parameters. As the consequence, various simplification results are generated. The simpler the output CAD model is, the less time is required. The detailed time consumption and simplification results are illustrated in Figure 11. Since current α-SIM utilizes the projection and extrusion strategy, only the features that are visible on 2D projections, such as the holes and outer profiles, can be preserved. The gear teeth and cavities can not be reconstructed using current α-SIM yet. Nevertheless, some solutions are already considered to handle these problems to generate a higher LOD simplification result. This will be discussed in next Section.

For comparison, the FRSM is carried out. A commercial software installed on the same desktop computer is used to perform this task. First, the automatic feature recognition is performed to recognize features from the B-rep model. Then various features are deleted manually to achieve different LOD results. Although the FRSM is more flexible since each feature can be suppressed individually provided the feature can be recognized, nevertheless while comparing with the α-SIM, the process is too time consuming, especially when the expected outputs have low LODs. In this example, the automatic feature recognition process already takes $200s$. Deleting features will consume more time. In addition to the time consumption, the recognition is failed to recognize some features, such as one of the teeth highlighted by red circles in Figure 11 and the screw thread presented in next Subsection.

4.4. Geometry simplification of a complex geometry model

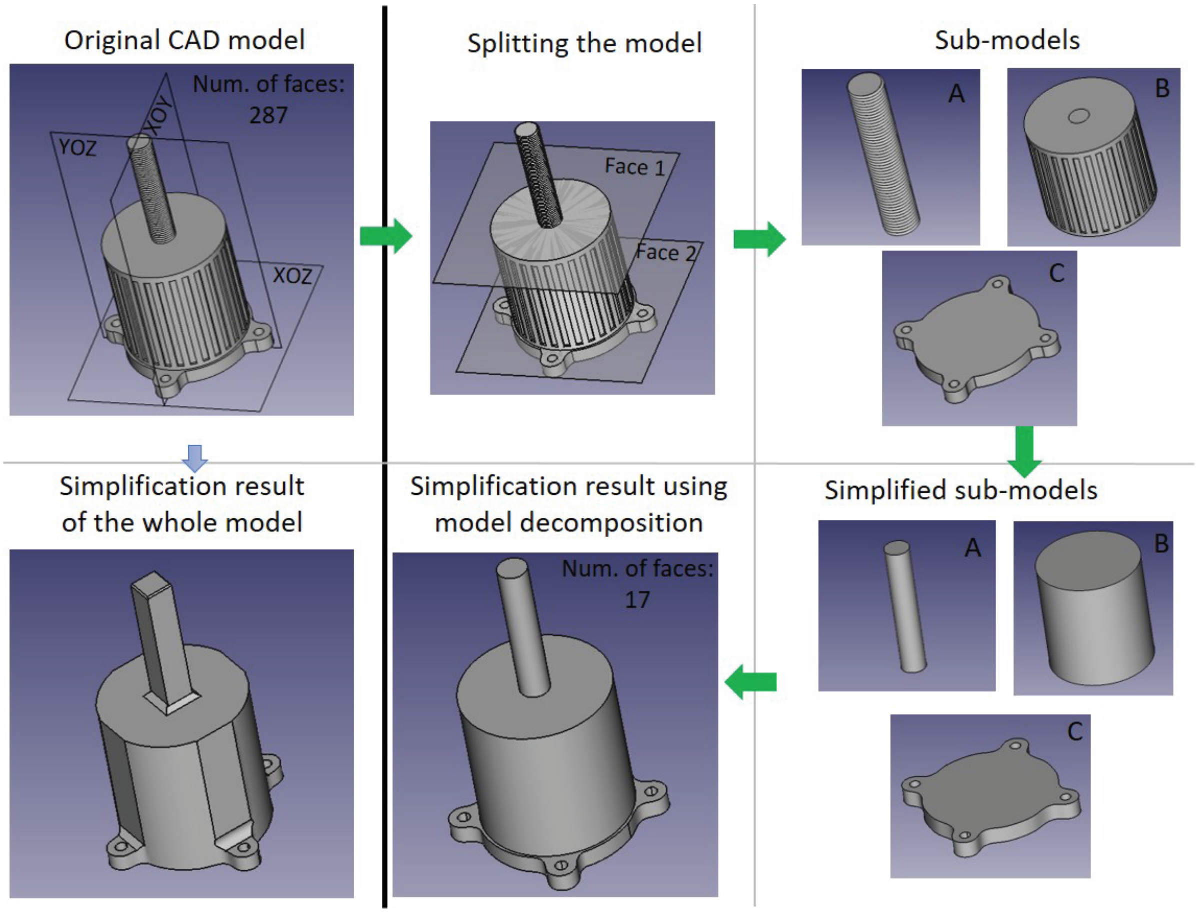

Figure 12: Simplification process of a complex geometry model

α-SIM relies on the 2D projection of 3D cloud points. Sometimes the features that should be preserved may be shielded by other parts of the model. For instance, as shown in Figure 12, the cylinder feature of the worm can not be reconstructed no matter how small the dim_{pre} is since its projection on XOZ is blocked by the motor. If the features of a model that are expected to be preserved can not be reconstructed from any 2D cloud points that are sampled with a sufficient small dim_{pre}, the model is called a complex model, such as the one here. Otherwise, the model is called a simple model. Whether a model is simple or complex does not only depends on the model itself, but also depends on the working scenarios. There has not a universal standard to evaluate this. Complex or not is determined by end users. For instance, the actuator here is a complex model since the cylinder feature of the worm needs to be preserved. However, a similar model in Figure 10 is considered as a simple one because the users do not think any key features are shielded by other parts of the model and they are more interested in the receptacle. A low level of detail approximation, such as the convex hull, is already sufficient for this application.

When a model is considered as a complex one, its satisfactory simplification can be achieved via decomposing the model into some simple models. In this test case, two faces are defined by the user and the actuator is then split into three parts by these faces. α-SIM is applied to each of the sub-models respectively. Finally, the sub-models are combined together using a Boolean union operation to generate a single CAD model. As shown in the right side of Figure 12, this result has a better approximation when comparing with the α-SIM result of the entire model.

During simplification of a complex geometry, the challenge task is how to define the faces to split the complex model. Currently, the faces are defined by the user manually. This hinders the full automation of α-SIM. Nevertheless, it has been noticed that these faces are located on some flat (planar) faces of the model. This means the faces of the model itself or faces reconstructed from coplanar 3D cloud points may be used as the splitting faces. This will be studied further in the future work.

5. Conclusions & Recommendations

This paper presents an innovative CAD model simplification method that is inspired by the descriptive geometry and the 3D modelling method using 2D sketches. The method is developed to handle the B-rep CAD models defined in the neutral data-exchange formats, such as STEP and IGES. The features' information and design sequence are not included in such file format. Instead of diving into low primitives, such as vertices, edges, and facets to recognize features, this method takes advantage of the 2D intuitive notional profiles of the actual CAD model to suppress the small features whose dimension is smaller than a threshold.

The simplification results can be outputted in the same data format as the input file. This trait enables embedding the simplification process into a (collaborative) product design work flow, such as cable and pipe routing, without any influence on the work flow. The test cases demonstrate that this method is able to generate geometry models at various level of details. The method is efficient comparing with the Feature Recognition and Suppression Method especially when the output has a lower LOD.

Although α-SIM already shows very promising application prospects for CAD model simplification, it can still be improved in the following aspects:

1. **Complex model decomposition**: as mentioned in Subsection 4.4, simplifying a complex CAD model does not lead to a satisfactory result, therefore some splitting faces are added manually to decompose a complex model for a better geometric approximation. The manual work is the bottleneck that hinders automating the α-SIM for a complex model. It has been noticed that the planar surfaces on a model can be used as the splitting faces or these faces can be reconstructed from coplanar 3D sample points. Further work needs to be done to work out an intelligent method generating these faces automatically.

2. **Various geometry sampling and reconstruction approach**: in this paper, projection and extrusion are utilized as a pair to support the 3D points sampling and reconstructing 3D models. Nevertheless, this pair does not work for all models. For instance, an entire fuselage or the helical gear can not be modelled by extruding a 2D sketch. Therefore different methods rather than the projection and extrusion are needed to take care of more generic CAD models. For instance, that a few 2D planes intersect a fuselage generate some 2D fuselage surfaces. The sample points on each surface can be easily obtained. Lofting the 2D α-Shapes constructed from each 2D sample points set will regenerate the fuselage, as how it is modelled.

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