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# Functionality-based part orientation for additive manufacturing

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## Abstract

Additive manufacturing (AM) is already diffused and well-accepted as a revolutionary method of manufacturing. The main advantage gained by using AM compared to conventional subtractive method is its capability to produce parts which have high shape complexity, different material composition, hierarchical complexity and functionality complexity. Besides, to be able to utilize fully the abilities of AM, specific design tools are needed. For example, the part orientation must be optimally defined before fabrication by AM. Several studies to optimize part orientation have been proposed. Indeed, aspects to optimize in the choice of the orientation include the minimization of the surface roughness, build time, need of supports, and the increase of the part stability in building process, but there are very few work related to the accuracy of the part. Despite all these considerations, they consider the part as a single component. AM instead can directly fabricate assemblies, such as mechanical joints. In this type of part, the most important feature is the assembly feature. As such, orientation consideration should mainly focus on these features and not necessarily the whole part. This paper proposes a method to orient a part considering all components as a functional assembly. A case study of universal U-joint is presented to validate the proposed methodology.

*Keywords*: Additive manufacturing; part orientation; curvature estimation; mesh segmentation; STL

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## 1. Introduction

Additive manufacturing (AM) is well-accepted a revolutionary method in manufacturing. AM technology offers the ability to realize a product having high shape complexity, different material compositions, high hierarchical complexity and functional complexity [1]. It is one of the enabler of mass customization and personal fabrication [2]. AM produces part in a layer-by-layer fashion, realizing very complex shape products non conventionally manufacturable, turning directly a computer aided design (CAD) model into a finished product often without any fixturing design [3]. To be used in AM the CAD model is converted into a triangle-mesh format, called Standard Triangulation Language (STL) format. Before the file is transferred to an AM machine, a file preparation step is carried out to optimize the build process, defining: part placement inside the working volume, support determination for overhang part, and part orientation.

The scheme of additive manufacturing from design to physical product by AM process is depicted in Fig. 1. From this figure, the process is explained as follow. First, a 3D model is designed using a CAD software. The file then is converted into STL format. Subsequently, a file preparation step is carried out to optimize the process, e.g. by determining part orientation, the position of the part inside the working volume, etc. Finally, the file is sent to an AM machine controller to start the fabrication process. The ability of AM to manufacture products with functional complexity means that this technology can directly produce assembled products [1],[5]. Therefore, the number of components required by a functional product can be reduced. Fig. 2 and 3 show an example of a universal-joint design for as manufactured by conventional and AM methods respectively. From these

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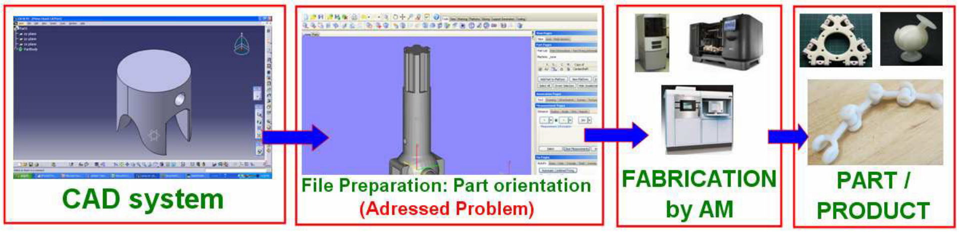

Fig. 1. Steps in AM from design to final part/product.

figures, it is worth noting that the total number of components, moving from conventional to AM method, reduces from seven to three.

### *1.1. Part orientation problem*

In this study, how to optimally orient a part for AM is addressed. The problem is a part of the file preparation stage in the AM process chain (Fig. 1). It is a relevant problem since the determination of part orientation is complex and time consuming due to many contradictive trade off which have to be considered, including surface quality and build time [4]. Different approaches yield different solutions, e.g. High volume of support materials will be needed if large area of surface is horizontally placed, instead in this condition the build time will be reduced since the number of layers will be less compared to that if the part is in vertical orientation. Usually, the proposed orientation optimizes some objective function related to the part functionality. Common objective functions to optimize the part orientation selection are to improve surface finish (reduce roughness), increase part strength in a specific direction, reduce support material, minimize build time and maximizing part geometric accuracy [6]. In the case AM manufactures an assembled product, part orientation should consider all the components constituting the product. This paper proposes a method to orient a part (representing an assembled product) considering all components as a functional assembly.

## 2. Existing part orientation methodology: state of the art

Many methods have been reported to optimize part orientation for fabrication by means of AM. Starting from 20 years ago, Cheng et al [7] optimized part orientation by optimizing two contradictive objective functions, maximizing surface accuracy and minimizing build time. The part analysis process was carried out from the CAD environment by means of a CAD interface library. The optimized orientation of the CAD file was then converted to an STL file and sliced. Pham et al [8] reported a method to orient a STL part by addressing the objective one-by-one. By this, the problem becomes a single objective optimization that is easier to solve compared to a multi-objective one. Their objective function included maximizing surface finish, minimizing support volume, minimizing build time. Masood et al [9] studied part orientation by minimizing the difference between CAD volume and built volume of prismatic part. The problem is a single objective optimization. They also studied part orientation optimization based on similar criteria for sculptured parts which is more general [10, 11]. The files used in their studies were both CAD and STL.

Heuristic search by genetic algorithm (GA) method to solve optimization problem of part orientation were used, especially the one with multiple objective function [12-20]. The common objectives were maximizing surface finish and minimizing build time. Additional objective beside these two were minimizing support needed for overhang feature [15], maximizing part stability in building process [16], minimizing post-processing time [18] and minimizing quantity of material used to fabricate a part [20]. Particle swarm optimization was utilized by Ghorpade et al [21] for objective function of optimal surface finish and build time. An iterative-based trust region method to solve the multi-objective function problem was used by Singhal et al [22]. All the optimization procedures for the multi-objective based part orientation were carried out on STL files.

Ahn et al [23] used GA to solve single objective optimization to orient a STL part fabricated by laminated object manufacturing. Their main goal was to minimize post machining time. A trust-region method was used by Singhal et al [24] to optimize surface finish as the single objective. They used STL file to carry out the analysis. Paul and Anand [25] used graphical technique to orient the part to increase the part accuracy. They used both CAD and STL file in their method.

The mentioned part orientation studies mostly concentrated on a single part and considered its whole part body to build. The question is if one builds a functional assembled product by AM, then the part analysis should be carried out for specific features of the whole assembly. In an assembly product, the most important features to guarantee the components can be assembled and functioning are its assembly features. Therefore, care should be taken mainly in the choice of the orientation of these features during AM. In this paper, we propose a method to determine assembly orientation by focusing on its assembly features to fabricate a functional assembled product. The feature considered is a cylindrical feature presenting a shaft-hole relationship. In a rotational join of shaft and hole, it is important that the surface quality of these features should have low roughness. Based on this consideration, the part orientation problem is addressed.

## 3. Functionality-based part orientation methodology

This section presents the methodology to optimize functionally the STL part orientation. The basic idea is to focus part orientation on the assembly features of components

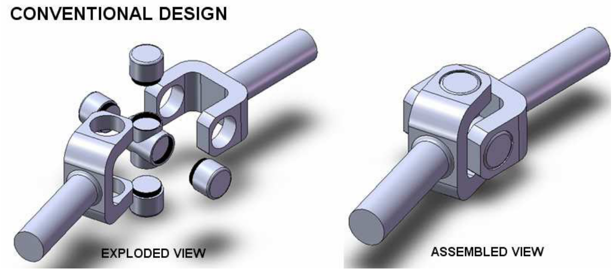

Fig. 2. Product design for conventional processes.

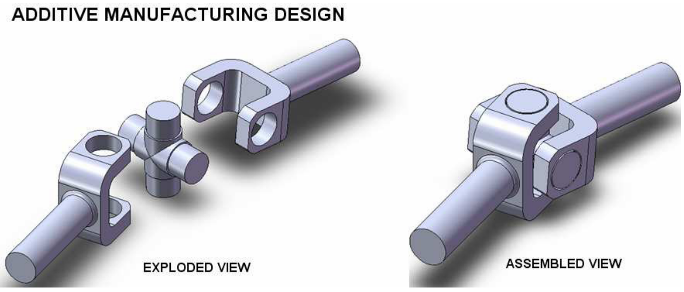

Fig. 3. Product design for additive manufacturing process.

to assure the functionality of the assembled product. Assembly features are those features through which components mate each other in a product with a specific functionality, such as gearbox, mechanical joint, etc. [25]. One of the most common assembly features is shaft and hole. This shape has a cylindrical surface and commonly presents a rotational joint. Based on this, the proposed methodology focuses on cylindrical features.

table 1: General steps of the methodology.

| | |
|---|---|
| **Input:** | Fix-Assembly design in STL format |
| **Output:** | Better part orientation considering assembly feature of rotational joint |
| **Procedure:** | *i. Feature Recognition* |
| | STEP 1: Point normal vector and curvature estimation |
| | STEP 2: Mesh Segmentation |
| | STEP 3: Identification of cylindrical feature |
| | *ii. Objective function calculation: Minimizing down/upward faces area of cylindrical feature* |
| | STEP 4: Calculation of down/upward triangle surface area. |

The general proposed methodology is presented in table 1. It consists of four main steps: *point normal and curvature estimation, mesh segmentation, identification of cylindrical surfaces, calculation of upward/downward surface area*. The required input for the methodology includes only the STL file of the fix-assembly product to manufacture. These steps are divided into two groups, which are feature recognition to identified face (triangle) belongs to a cylindrical surface and objective function calculation. The objective is to select an orientation in which the area of down/upward faces is minimum. Downward or upward face is a face which has orientation other than vertical or horizontal direction. This is because a low roughness of the cylindrical surface will be obtained if these types of face area are minimized. Detailed procedure is explained as follows.

### 3.1. Point normal vector and curvature estimation

Before calculating the curvature the normal of each point should be calculated. The normal of point $\mathbf{p_i}$ is calculated as:

$$\sum_{i=1}^{n} \mathbf{nf_i}/\mathbf{n} \qquad (1)$$

where n is number of adjacent triangles and $\mathbf{nf_i}$ is the normal of triangle **i** (fig. 4). The Next step is the curvature estimation for each point $\mathbf{p_i}$ (see fig. 5). This step is required for the mesh segmentation procedure. It mainly follows Hamann method [26] by fitting a quadratic surface to adjacent points and deriving the two principal curvatures from it. The estimation is explained as follows. For each point $\mathbf{p_i}$, plane $PL_i$ is determined by:

$$\mathbf{n_{pi}} \bullet (\mathbf{x} - \mathbf{p_i}) = 0 \qquad (2)$$

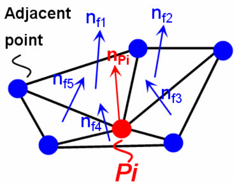

Fig. 4. Determination of point's normal vector.

Then, **Platelet**-$j_i$, which are points sharing an edge with $\mathbf{p_i}$, are projected on $PL_i$. This projected point is called **platelet**$^p$-$j_i$ and calculated as:

$$\mathbf{Platelet^{P}}_{\mathbf{ji}} = \mathbf{Platelet}_{\mathbf{ji}} - d_{ji}\mathbf{n} \tag{3}$$

where $d_{ji}$ is orthogonal distance of Platelet-j$_i$ to plane PL$_i$. $d_{ji}$ is calculated as $d_{ji} = \mathbf{n}_{\mathbf{pi}} \bullet (\mathbf{x} - \mathbf{p}_{\mathbf{i}}) / \|\mathbf{n}_{\mathbf{pi}}\|$. Each point of **platelet**$^{P}$-j$_i$ is translated to coordinate system centered on $\mathbf{p}_{\mathbf{i}}$. **<ui,vi>** are basis vectors defining its reference system. In order to do this, a difference vector $\mathbf{d}_{\mathbf{ji}}$ between **platelet**$^{P}$-j$_i$ and $\mathbf{p}_{\mathbf{i}}$ has to be calculated as:

$$\mathbf{d}_{\mathbf{ji}} = \mathbf{Platelet^{P}}_{\mathbf{ji}} - \mathbf{p}_{\mathbf{i}} \tag{4}$$

The difference vector $\mathbf{d}_{\mathbf{j}}$ can be represented in **<u,v>** basis as:

$$\mathbf{d}_{\mathbf{ji}} = (\mathbf{d}_{\mathbf{ji}}.\mathbf{u})\mathbf{u} + (\mathbf{d}_{\mathbf{ji}}.\mathbf{v})\mathbf{v} \tag{5}$$

Therefore, the local coordinate of **platelet**$^{P}$-j$_i$ based on **<u,v>** is:

$$(p_{ji}, q_{ji})^{T} = (\mathbf{d}_{\mathbf{ji}}.\mathbf{u}, \mathbf{d}_{\mathbf{ji}}.\mathbf{v})^{T} \tag{6}$$

The next step is to fit a quadratic surface to **Platelet**-j$_i$ having abscissa of $(p_{ji}, q_{ji})^{T}$ and ordinate of $d_{ji}$. The surface is formulated as:

$$f(p,q)_i = \frac{1}{2}\left(c_1 p_{ji}^{\;2} + 2c_2 p_{ji} q_{ji} + c_3 q_{ji}^{\;2}\right) \tag{7}$$

From this equation, one can observed that the minimum or maximum point of the surface will be at point $\mathbf{p}_{\mathbf{i}}$. The equation can be represented in Matrix form as:

$$\begin{bmatrix} p_{1i}^2 & 2p_{1i}q_{1i} & q_{1i}^2 \\ \vdots & \vdots & \vdots \\ p_{ni}^2 & 2p_{ni}q_{ni} & q_{ni}^2 \end{bmatrix} \begin{bmatrix} c_{1i} \\ c_{2i} \\ c_{3i} \end{bmatrix} = \begin{bmatrix} d_{1i} \\ \vdots \\ d_{ni} \end{bmatrix} \tag{8}$$

Solving eq. (8) by least squares yield an estimate of $c_{1i}, c_{2i}, c_{3i}$. The two principle curvatures $k_{1i}, k_{2i}$ of the fitted surface are derived by calculating the two roots of equation:

$$k_i^{\;2} - (c_{1i} + c_{3i})k_i + c_{1i}c_{3i} - c_{2i}^2 \tag{9}$$

Finally, Gaussian curvature $K_i$ of a point $\mathbf{p}_{\mathbf{i}}$ is calculated as $K_i = k_{i1}k_{i2}$.

### *3.2. Mesh segmentation*

After the point curvature has been estimated, mesh segmentation procedure is carried out. The main goal is to identify a group of triangles which share the same region. Similarity criteria for adjacent triangles to be in the same region are:

- $K_i < T_{curv} = 0.4$. Gaussian curvature of a sharp edge will have value < 0, but since there is a numerical approximation to fit the surface, the value is shifted.
- $\forall$ Angle between two triangles$\in$ the same region $< T_{angle} = 20$. The STL file is derived from nominal CAD model. Surfaces in different face segment will have relatively larger normal angle (perpendicular surface, fillet, etc).

Fig. 6 presents illustration of the mesh segmentation process. The procedure of mesh segmentation process is explained as follows. For all un-labeled face-*i* (triangle), label the face-*i* with a new group. Then, all faces adjacent to face-*i* are identified. If the criteria for inclusion in the same region are met between face-i and the adjacent faces, then label the adjacent faces with the same label with face-*i*. The adjacent faces with the same label are stored in a stack. Subsequently, for all faces inside the stack, their adjacent faces are scanned and similarity is measured. If the similarity measure is followed, then label the adjacent face with the same label of the face inside the stack of which it adjacent to. Next, a new unlabeled face-*j* from the set of un-labeled face (triangles) are scanned and given a new label. Identical procedure to grow the region is carried out until all adjacent faces relative face-*j* are labeled. These iterative processes are repeated until all faces are labeled.

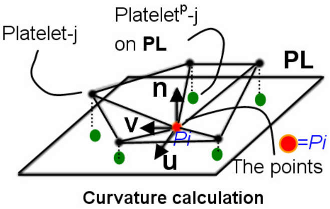

Fig. 5. Illustration of the curvature calculation procedure.

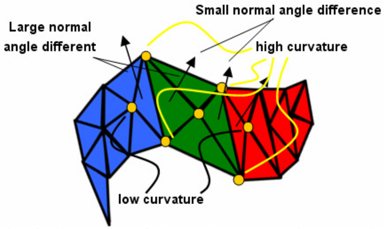

Fig. 6. Illustration of the mesh segmentation procedure.

### *3.3. Identification of cylindrical surface*

After the mesh segmentation procedure, identification of the assembly feature, in this case cylindrical feature, is carried out. To determine faces (triangles) which belong to a cylindrical surface, angle between two opposite faces in the same region (identical label) is calculated. If for all faces inside the region, there is exist its pair opposite face, which have angle between them approximately $180^0$ (>$175^0$) and for all area of face inside the region are similar, then the mesh (triangle) region is identified as a cylindrical surface and the region is labeled as cylindrical. These procedure is repeated until all segmented mesh have been identified either as cylindrical or non-cylindrical features. Fig. 7a depicts the identification of cylindrical features by checking the angle between two opposite faces.

### *3.4. Calculation of upward/downward surfaces area*

Finally, for all faces belong to cylindrical feature are classified whether they are horizontal, vertical, downward sloping or upward sloping area (fig. 7b). The idea is that commonly moving assembly product use shaft-hole relationship. For this reason, in order to reduce friction, the surface of cylindrical feature should be smooth. Subsequently, the optimization is to minimize area of upward and downward sloping face area of the cylindrical surface. Because, the higher the area of these types of surface, the larger the stair case effect induced by AM process. In addition, for downward sloping faces, support material is needed. Removing supports increases the roughness of the surface. The identification of upward/downward faces is obtained by checking their normal vector angle, having angle > $\pm 5^0$ (threshold value) from vertical (0,0,1) and horizontal (1,0,0) vectors.

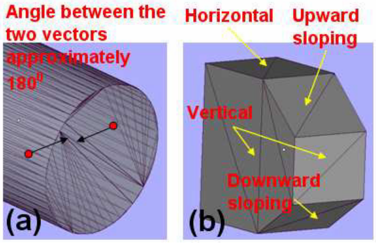

Fig. 7. (a) Determination of cylindrical surface, (b) Type of surface direction.

## 4. Case study: Universal joint (U-Joint)

The case study selects U-joint to validate the proposed methodology. The U-joint, designed for AM process, is shown in fig. 3. Three components, two shafts and one joint constitute the assembly. The segmentation procedure is verified by applying to each STL file of the joint and the shaft. Fig. 8 and fig. 9 show the segmentation result to detect cylindrical surface for the joint and the shaft, respectively. From these figures, it can be observed that the cylindrical surface can be isolated (segmented) out from other type of surfaces (red color). It can be observed that the long cylinder in the shaft (fig. 9) is not considered as cylindrical surface since it has filleted-face on its edge.

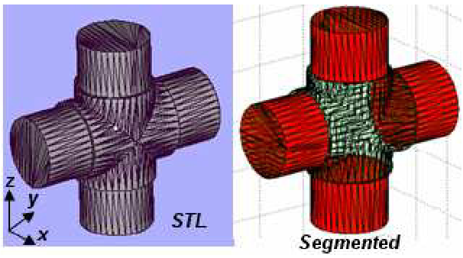

Fig. 8. STL and segmented file of the joint.

After the segmentation verification, the proposed procedure for part orientation is applied to the whole assembly. Fig. 10 presents results of part orientation considering the assembly features to additively fabricate a functional assembled product. There are two different orientations demonstrated. The first orientation (fig. 10a) of the assembly is horizontally placed. In this orientation, the total upward/downward sloping face area for the cylindrical features is 5150 mm$^2$ and the total upward/downward sloping face area, for all the parts (three parts), is 40089 mm$^2$. In fig. 10b, a vertically placed orientation is applied to the assembled U-joint. In this orientation, total of 10241 mm$^2$ of downward/upward sloping face area is obtained. The total downward/upward sloping face area by considering all the three parts is 34482 mm$^2$. Based on these two types of orientations, different decisions to select the best placement for AM process are observed. Based on functionality of the assembled product, one can chose horizontal orientation for fabrication by AM. But, if one considers the surface quality of all parts of the assembled U-joint, vertical orientation will be selected. Table 2 shows the summary of the calculated area of the sloping faces for both horizontal and vertical directions.

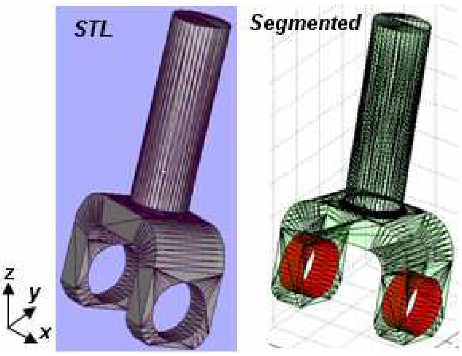

Fig. 9. STL and segmented file of the shaft.

Table 2. Results of calculated sloping face area for different type of orientation.

| Orientation | Sloping area | |
|---|---|---|
| | Total parts [mm$^2$] | cylindrical surface [mm$^2$] |
| Horizontal | 40089 | 5150 |
| Vertical | 34482 | 10241 |

## 5. Conclusions

In this paper, the importance of part orientation procedure in AM process is explained. This procedure significantly affects the final fabricated part/product. Since AM process can fabricate functioning assembled products, the part orientation should consider all the parts as an assembly. In assembly, the assembly features are the one determining the success of the assembly of the components. Because of this, a functionality based part orientation methodology is proposed. The methodology focuses on the assembly features while considering the part orientation. Cylindrical feature is selected for this study since it represents the common shaft-hole relation to mate parts. Results show that the final recommended part orientation is different should one consider either only single part or the whole (assembled) parts together. Future work will aim at considering other type of

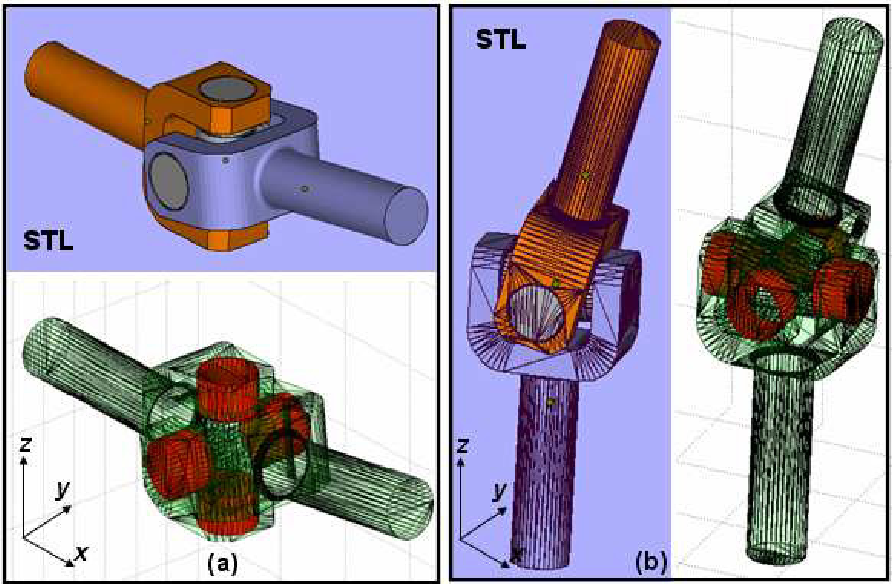

Fig. 10. (a) Horizontal orientation, (b) vertical orientation. Red area is the segmented assembly features, which is cylindrical features.

assembly features and other type of objective function, such as geometrical accuracy in optimizing part orientation for AM fabrication and exploring potential of general part orientation method directly from the CAD system.

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