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Design for additive manufacturing: Automated build orientation selection and optimization

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Abstract

Additive manufacturing, or 3D printing, is an emerging type of production technology that is seen as the core technology for future high-value engineered products. Due to the additive nature of stacking and unifying individual layers, the part and process design is substantially different from conventional production methods. This paper addresses one of the challenging design aspects for additive manufacturing, namely the determination of the build orientation. The build orientation has a large impact on the final part quality and must therefore be chosen wisely. This paper presents an approach to support the build orientation selection by a feature-based design algorithm. After automated part tessellation and the detection of outer part surfaces, the algorithm determines candidate build orientations through a ray-tracing and convex hull method. Candidate solutions are ranked based on minimizing overhang structures, as this also minimizes the need for additional support structures.

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Keywords: Design tools; Computer aided process planning; CAD/CAM; Additive Manufacturing; 3D printing

1. Introduction

Additive Manufacturing (AM), colloquially known as 3D printing, is positioned as an advanced manufacturing technology and as the future core technology for high-value engineered products in European as well as US research agendas [1, 2]. Due to the additive nature of the manufacturing process, it has great potential for producing parts with complex geometries and integrated functionalities. Also, since it is a Direct Digital Manufacturing (DDM) method, individually customized parts can be made with relative ease [3]. The technology is widely applicable to industries, such as aerospace [4], automotive and healthcare [5], but also more general for logistics and maintenance [6]. The interest in AM has gained considerable impetus over the past decade. The development of AM is provided by the needs of industry to exploit the beneficial effects of these manufacturing techniques. Beneficial effects, or competitive advantages, of AM are geometrical freedom, shortened design-to-product time, reduction in process steps, mass customization and material flexibility [7].

In 2010 the American Society for Testing and Materials (ASTM) has standardized AM technology according to seven categories depending on the method of manufacturing each layer [8]. However, in general, 3D design data is used to build up parts by binding raw material, e.g. a fine powder, layer by layer, stacking layers until the full 3D geometry is ready [9]. This is illustrated in Fig. 1 for a powder-bed technology, in which the powder is fused by means of a laser. After fusing one layer, the unfinished part in the build area moves down and a new layer of powder is rolled on top of the previous one. This process is repeated until the part is finished. The powder is only fused together where needed using the part's computer model directly.

One of the crucial choices during production is the selection of the build orientation. As the build orientation has a large impact on the final part quality, it must be chosen wisely. At present, the selection, let alone optimization, of the build orientation is ill supported by computer tools. It is usually a manual operation requiring professional craftsmanship and operator skills.

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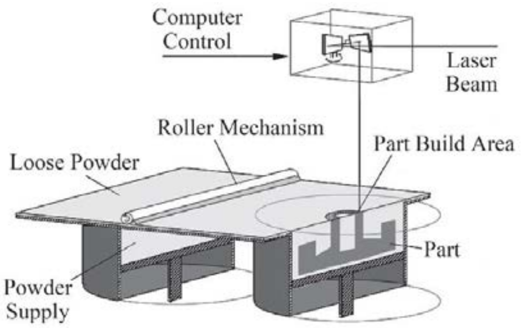


Fig. 1: Layer stacking process for a powder-bed technology [10].

1.1. Design for additive manufacturing

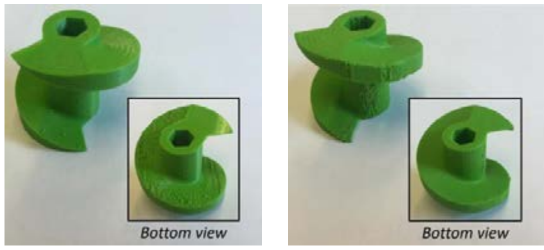
When designing an AM part in general the following 3-step approach is adopted [11]:

1. The part to be produced is modeled on a Computer-Aided Design (CAD) system. The model must be represented as closed surfaces which unambiguously define an enclosed volume. This requirement ensures that all horizontal or vertical cross sections that are essential for AM are closed curves to create the solid object.
2. The computer model is converted to a STereoLithography (STL) file format. This is currently the industry standard for transferring information to AM equipment, although a new Additive Manufacturing File (AMF) format is being promoted. The STL model describes only the surface geometry of a 3D object without any representation of color, material, texture or other common CAD model attributes. The AMF format is indeed capable of handling more than only surface geometry [12].
3. The STL model is prepared to be sent to the AM equipment using a Computer-Aided Manufacturing (CAM) system. This can be a proprietary system and file format, e.g. SLM code. However, some technologies also use an open standard, e.g. G-code. Generally the preparation consists of setting process parameters for the specific AM technology; e.g. build orientation, part slicing, build platform positioning, design of support structures, layer solidification parameters, etc.

In this paper, Step 1 is considered part design and Steps 2-3 are considered process design, and the emphasis is on Step 3 in which amongst others the build orientation is selected.

To exemplify the effects of the build orientation selection Fig. 2 depicts two screw spindles. In both cases the CAD design and STL model of Steps 1-2, respectively, are identical. The only difference is the selection of the build orientation (Step 3). In Fig. 2(a) the build direction was chosen along the axis of rotation. This mend the screw had to be supported underneath the entire rotation. In Fig. 2(b) the build direction was chosen radially. In this case the internal slot, connecting the spindle to the rod, and one side of the screw had to be supported.

These images show that the build orientation selection has an influence on the final part geometry, and thus part quality. Depending on the type of AM technology the exhibited flaws may be different. In this case Fused Deposition Modeling (FDM) was used, causing the first layers to sink in towards the flat bottom plate. This leads to a lower quality of the outer circular shape and internal slot as can be seen in Fig. 2(b). On the other hand, Fig. 2(a) shows the degradation of surface quality on the bottom (supported) side of the screw (see bottom view insert).



a) printed along the axis of spindle b) printed radially

Fig. 2: Effect of build orientation selection for fused deposition modeling.

1.2. Goal and outline

The goal of this paper is to present a framework in which the build orientation selection is automated using a feature-based design algorithm. The developed design tool provides information on the effects of the build orientation. As the algorithm provides relatively quick insights, the tool can be used for build orientation optimization strategies as well. The design tool is capable of ranking candidate solutions based on minimizing overhang structures, as this effect is common among a range of AM technologies. In general, minimizing overhang structures minimizes the need for additional support structures. Consequently better part quality can be attained, as overhang structures typically feature a relatively poor surface quality; e.g. a high surface roughness.

The paper is structures as follows. In Chapter 2, based on a literature study of other researchers in the field, the developed five-step algorithm to support the build orientation selection is presented. In Chapter 3 the algorithm is applied in a case-study example to demonstrate the working principle. In Chapter 4 the design tool is discussed and the future potential of the followed approach are reviewed. Finally, in Chapter 5 the conclusions are presented.

2. Approach

In the last years, a number of authors have proposed different methods for minimizing the amount of support structure by reducing the overall overhang. Allen and Dutta [13] computed the amount of support structure required using a facet normal approach for a given orientation and thus identifying a pool of good candidate orientations. Strano et al. [14] used the same approach but accelerated the computational time by calculating the support at every 5° of rotational angle about x and y axes. This method may not find the optimum orientation, especially when considering very complex structures that typically originate from part topology optimization strategies. Other algorithms use the rendering abilities of GPUs to map the depth value of planes to compute the amount of support volume needed (Ezair et al. [15]) or use a voxel-based algorithm to calculated for each column of voxels the empty voxels in order to determine the amount of support structure needed (Paul and Anand [16]). Finally, Morgan et al. [17] proposed a single objective optimisation technique to find the best build orientation of the part in order to minimise the volume of support needed during the build.

The algorithm proposed in this paper uses the convex hull principle and the angle between outward unit normal of the (triangle) surface to determine the optimal build orientation for the minimization of support structures. This approach allows from the optimization of convex as well as concave parts. The algorithm for the build orientation selection can be divided in five steps, as shown in the block diagram of Fig. 3.

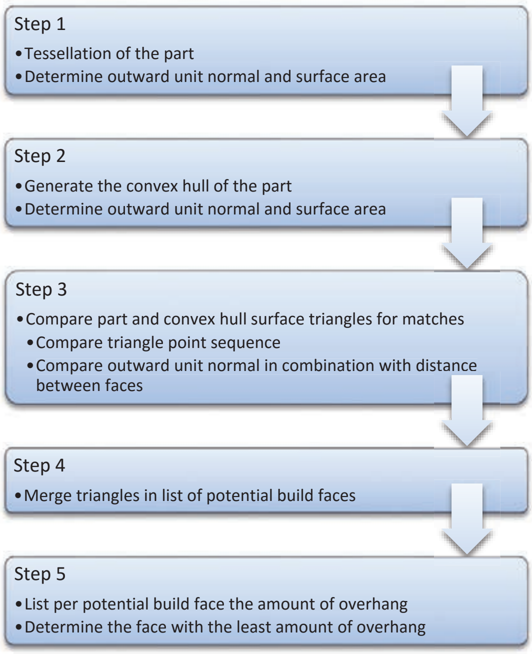


Fig. 3: Five-step algorithm to support the build orientation selection.

In Step 1 standardized part tessellation is performed on a part's CAD model, creating a triangulated surface mesh of the part. Also, the outward unit normal and surface area of each surface triangle are calculated in this first step of the algorithm. This information is further used in Steps 3-4.

In Step 2, the algorithm uses the convex hull principle to determine the points of the tessellated part that are situated on the convex outside surface (hull) of the part. If the face is not an element of the convex hull, it must be part of a cavity or (internal) hole. The face can therefore not serve as surface to start the build job from. In this case, the convex hull routine of Matlab is used to determine the complying points. The trimesh routine is used to make the tessellated convex hull of these points. Similar to Step 1, the outward unit normal and surface area of each surface triangle are calculated.

Step 3 is the most challenging step in the selection of the optimal build orientation algorithm. The triangulated surface mesh of the part and convex hull must be compared in order to determine which faces of the part are on the convex hull. This comparison is done in two stages.

In the first stage the point sequence representing each surface triangle of the part is compared against all point sequences of the surface triangles of the convex hull. If there is a match, the surface triangle is added to the list of potential build faces. When there is no similarity, the surface triangle of the part could still be an element of the convex hull due to the different tessellation routines. Fig. 4 shows the surface tessellation of the part in black and that of the convex hull in red. As can be seen, there are a number of elements of the black triangles visible despite the fact that all original points of the part are on the convex hull.

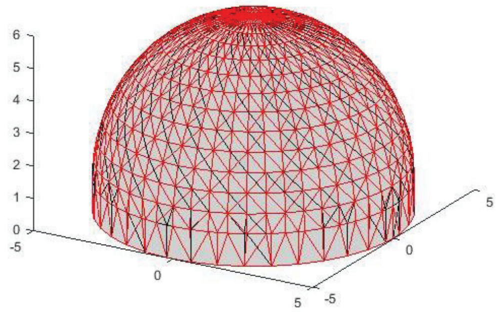


Fig. 4: Surface tessellation (black) and convex hull (red).

In the second stage this difference in tessellation is solved by comparing the outward unit normal in combination with the distance. Comparing only the three points of a part surface triangle with the list of points on the convex hull will result in the addition of holes on the surfaces to the list of potential build faces. Therefore, first the unit normal of a part face is compared with the unit normal of all convex hull faces. If the two unit normals match within a specific tolerance, the distance between the two faces is determined. In this case, up to a couple of degrees for the angle between these two unit normals is sufficient. If this distance is less than the set tolerance, the face must be part of the convex hull and was not detected in an earlier stage as a result of the differences in tessellation routines. Step 3 finally results in a complete list of potential triangles from where the part can be oriented for possible best-build directions. The list contains only triangles from the original tessellated CAD part.

Step 4 of the algorithm is to check whether the triangles in the list of potential build faces can be merged into a larger surface; for instance, a flat rectangular surface is always divided into two triangles by tessellation. This merging of triangles is done based on the outward unit normal of faces. There is no need to check the distance as was done in Step 3 since the list only contains outer faces with unique outward unit normals except for faces that are parallel. Besides the merging of triangles in the list of potential build faces, the internal faces are also merged based on their orientation.

In the final Step 5, the amount of overhang is calculated for each potential build orientation (surface consisting out of one or more triangles). The angle between the outward unit normal of this build 'surface' and each internal surface is determined. If this angle is larger than a prescribed angle, the internal surface is considered an overhang and will need an additional support structure to ensure the shape stays correct during the AM process. When an internal surface is qualified as overhang, the projected surface area of this surface is added to the total amount of surface overhang created when the part would be manufactured using this specific build surface. The total amount of surface overhang per potential building surface is divided by the surface area of this building surface and listed. The build surface with the minimum of overhang and with the beneficially highest surface area will have the lowest value in this list. This surface would give the best build orientation with regard to overhang and minimized the support structure.

3. Case-study example

The working of the algorithm is demonstrated in a case-study example for a non-functional 3D surface part, as shown in Fig. 5.

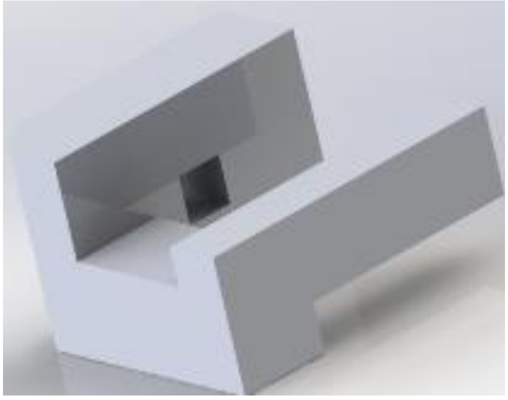


Fig. 5: Case-study 3D part in CAD file format.

The surface of the object consists of 86 triangles for Step 1 of the algorithm. The part has several cavities and angled faces. Fig. 6 shows the part surface tessellation in black of Step 1. The convex hull of Step 2 is superimposed over the part in red.

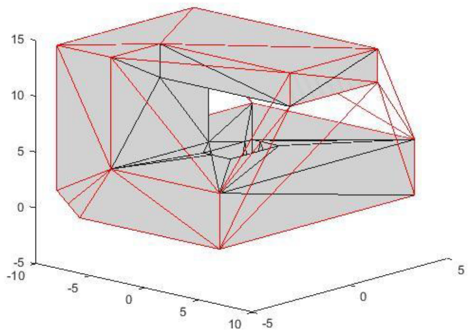


Fig. 6: Surface tessellation (black) and convex hull (red) for a 3D part.

In Step 3 of the algorithm the comparison between the surface tessellation of the part and the convex hull is done in order to determine suitable faces to start the build job from. The red faces in Fig. 7 are the faces that are not part of the convex hull; the grey faces are therefore the remaining candidates.

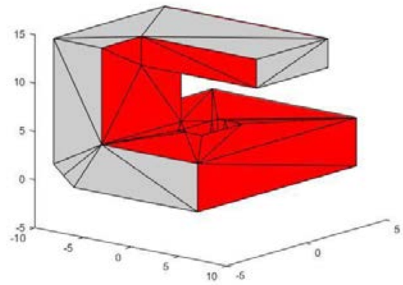


Fig. 7: Non-convex hull faces in red; possible candidates in grey.

Finally, Fig. 8 shows the results after the final Step 5 of the algorithm. The best group of faces to use as base to start the build job from providing minimal overhang are colored red. The second and third best groups of faces are colored green and blue, respectively.

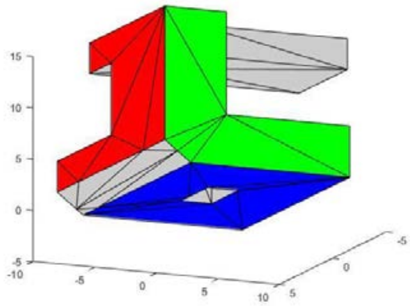


Fig. 8: Best potential surfaces to start the build job in red, green and blue, respectively.

Examining the results of the algorithm, the red surface gives the least amount of support structure. Using the red surface as surface to build from, the hole and chamfer (43.6° angle with the red surface) need additional support. The algorithm can be further tested by slightly adapting the part. For instance, when the angle of the chamfer is adjusted to 45 degrees, which is a common maximum build angle for AM, the part can be built from the chamfer surface without additional support structures. This is shown in Fig. 9 in which the red surface is now the best surface to start building the adapted part. Also, the green and blue surfaces have been adapted accordingly. As expected the best surface to start building the part is now the chamfer surface. This shows that the algorithm is able to handle small changes in part geometry that clearly make a difference in selecting the best surface to build from.

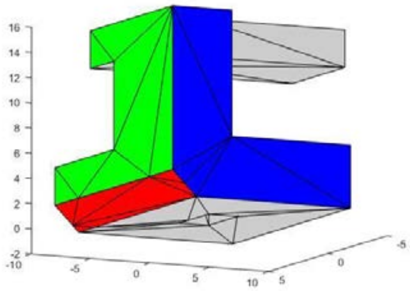


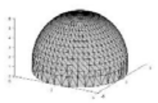
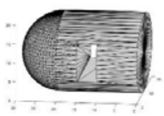
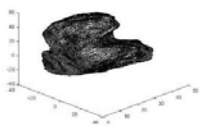
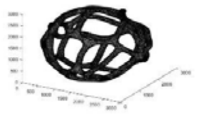
Fig. 9: Best build surface indicated in red for the adapted part.

The total processing time for computing and ranking best-build orientation candidates in the case-study of Figures 5-9 was approximately 0.21s for both situations (i.e. original and adapted parts). The algorithm was programmed in Matlab and ran on an Intel Core i5-3437U @2.4 GHz and 4 GB RAM.

4. Discussion and design tool potential

The presented case study demonstrated that the proposed algorithm can predict the optimal print orientation for a concaved part. Several more complex parts have been investigated. Table 1 lists the number of tessellation triangles and the computation time for these parts.

Table 1: Comparison of the number of tessellation triangles and the computational time for various part designs with increasing complexity.

Part design	Triangles	Processing time [s]
	1500	4.9
	3034	28.8
	9774	40.4
	36,060	465.5

The results of the case-study are also compared with existing algorithms. Most of the algorithms found in the literature [13-14, 16] use a predetermined angle of rotation; in many cases steps of 5 degrees are taken. The angle is an optimization between the relative error percentage regarding the real best print orientation and the computational time. This makes most of the aforementioned algorithms faster than the proposed algorithm of this paper. However, the results when applying a systematic rotation strongly depends on the (arbitrary) starting orientation of the part and the algorithm may not find the best orientation when considering more complex parts. For the adapted case-study part shown in Section 3, the orientation analysis of a commonly used program such as Meshmixer by Autodesk is not able to detect the chamfer as best print orientation due to the predetermined angle of rotation that is used. This is demonstrated in Fig. 10, in which a screenshot is presented that shown the best build orientation according this program.

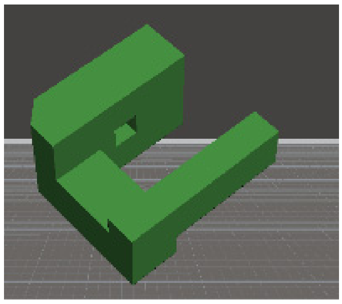


Fig. 10: Best print orientation of the adapted part according to Meshmixer by Autodesk.

As the proposed algorithm on this paper is not based on a (predetermined) fixed angle of rotation, the computational time is generally longer, especially when the number of triangles increases or the geometry of the part becomes more complex. This particularly holds for Step 3 of the algorithm in which the faces of the part that are on the convex hull are detected. Round and spherical surfaces especially require many iteration steps. Due to this the algorithm has, in the worst case, a complexity order of $O(n^2)$. On the other hand, when the algorithm is compared to similar algorithms (i.e. without a fixed angle of rotation), as e.g. the algorithm of Morgan et al. [17], the proposed algorithm performs relatively fast.

The computation time can be further reduced by improving Steps 2-3 of the algorithm. For instance, instead of using a standard Matlab routine for the tessellation of the convex hull a custom routine can take the original tessellation of the part (Step 1) into account, possibly making Step 3 unnecessary. Also, the sequential structure of the algorithm can be rearranged to include more parallel structures that are favorable for GPU accelerated computing.

Next to the detection of overhang structures, the algorithm can be expanded to detect outer features as well. For instance, part deformation related to a particular build orientation in combination with geometric tolerances, as was illustrated in Fig. 2, can be evaluated as well. Similarly expected surface quality can be evaluated as a function of the build orientation.

Other dependencies that can be taken into account are optimal surfaces to attach fixtures for the post-processing of particular part features, such as hole drilling, thread tapping, surface smoothening, geometric tolerances, etc. This is particularly worthwhile for enhancing the entire manufacturing process, as post-processing is very common for AM.

The final challenges would be to establish a working set of weighing factors to compare the different part features. As this may differ per design case, the merit of the developed tooling is the efficiency in which the results of a design process decision can be related to the final part quality. The ultimate goal for the design tool is to have real-time monitoring of the effects of the process design, when working on the part design.

5. Conclusions

This paper presents an approach to support the selection of the build orientation; one of the challenging process design aspects for additively manufactured parts. The developed algorithm is capable of finding the best build orientation in combination with the largest print surface for stability. The novelty in this approach lies in the fact that the results are not limited by pre-fixed intervals of rotation angles about the x and y axes. As the developed design tool provides relatively quick insight information on the effects of a chosen build orientation, the tool can be used for build orientation optimization strategies and part design optimization for AM as well.

The selection algorithm takes the original digital (CAD) design of a part and performs a number of automated steps, including part tessellation, creating an outer part convex hull, comparing and merging triangles on the outer faces of the part, and finally computing the build orientation for a minimum amount of overhang structures based on a ray-tracing method. Candidate solutions are ranked and visually presented to the designer, which gives a better understanding of the process design solution space.

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