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Deterministic part orientation in additive manufacturing using feature recognition

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Abstract

Additive Manufacturing (AM) is becoming an integral part of modern manufacturing systems and therefore, the AM technologies needs to adhere to strict quality demands. Due to the layered nature of AM, the part build orientation has a major influence on final part properties. Previous efforts to optimize the part orientation largely utilizes evolutionary algorithms, which are stochastic in nature. This paper argues for a deterministic solution to facilitate automation and standardization, and proposes a method utilizing feature recognition for faster computation. A case study for selective lase sintering is presented to demonstrate the feasibility of the proposed method.

Keywords: Additive Manufacturing; Optimization; Surface; Quality; Computer Automated Process; Part Orientation

1. Introduction

The concept of additive manufacturing (AM) had its genesis in 1986 when the stereolithography apparatus (SLA) was first patented by Hull and later commercialized by 3D Systems [1, 2]. Since then, AM has developed from manufacturing of physical (but non-functional) prototypes reducing time-to-market, to an entire family of technologies [3]. The AM concept encompass processes capable of producing anything from multicolored models to functional parts for end use in a variety of materials [4]. These versatile areas of application make AM increasingly popular in manufacturing industry. From 2010 to 2015, an annual growth of approximately 30% was recorded, and the industry show no signs of regressing any time soon [5].

As the industrial sector continues to embrace the technology, the need for efficiency is increasing. Subsequently, this necessitates research in several areas of AM, one of which is the automatic optimization of part orientation [6]. The orientation of the part during additive manufacture affects not only the build height, which in turn affects the build time [7], but also surface quality [8], part accuracy [9] and mechanical properties [10]. For technologies that require support structures, the need for such structures can also be reduced by a proper part build orientation [11]. This means that a suitable orientation can save time, material, and energy – all of which ultimately contributes to a reduction of total cost [12].

Existing solutions to the orientation problem extensively utilizes evolutionary algorithms (EAs) to converge to a solution. The stochastic nature of EAs introduces variability to the manufacturing process, which in the spirit of standardization and automation is a suboptimal solution. This paper proposes a novel non-stochastic method for determining the part build orientation using the basic geometric features of a part.

2. Related work

Since the middle of the 1990s, researchers have developed methods for optimizing part orientation in AM [13]. Frank and Fadel [7] developed an expert system for SLA that guided the user to the orientation with minimal staircase effect and additionally minimized build time and support structures. Cheng, et al. [9] developed a multi-objective optimization method for finding the orientation

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for a single part in SLA and fused deposition modelling (FDM). The authors considered part accuracy and build time by comparing all orientations yielding a planar surface that could be used as a base for beginning the build process. Xu, et al. [14] ensured part stability in SLA by proper orientation, and further improved part accuracy by working directly on the CAD (Computer Aided Design)-model and introduced an adaptive variable thickness slicer. The authors later considered build cost as the main objective for the technologies SLA, FDM, selective laser sintering (SLS), and layered object manufacturing (LOM) [12].

Masood, et al. [15] introduced volumetric error as an estimation of volumetric difference between the STL-file and the final part assuming sharp edges in FDM. The concept was applied to cones and pyramids [16], before more complex parts were investigated by rotation at certain increments about user specified axes [17, 18]. Because of the difficulties of correctly modelling the edge of each layer, several proposals are found in the literature. As an alternative to volumetric error, Lin, et al. [19] developed a mathematical model for comparing layered process error imposed by the staircase effect of several candidate orientations.

Byun and Lee [20] proposed average weighted surface roughness as another measure of surface quality assuming round edges. The authors used a genetic algorithm (GA) to optimize the weighted objective function considering surface roughness and build time. Later, the authors included build cost and variable slicing in the consideration [21], and also made recommendations on what technology to use for fabrication [22].

Paul and Anand [23] introduced tolerances to the optimization objectives by including cylindricity error. Later, Geometric Dimensioning and Tolerancing (GD&T) was further investigated as cylindricity and flatness error was considered together with support volume [24]. Das, et al. [11] utilized unit spheres to visualize how tolerances and support volume was affected by part orientation, and later used a combination of an exhaustive search and GA to solve the optimization problem [6].

Zhang and Bernard [25] proposed using AM features as the foundation for part orientation before a multi-attribute decision making method is applied to arrive at the final solution [26]. The authors further develop the method to rotate 16 parts simultaneously by applying a GA [27], and optimize orientation in FDM for continuous fibers [28]. Furthermore, the authors developed a facet clustering method as an alternative to feature recognition for accelerating subsequent computation [29, 30]. Quite recently, Delfs, et al. [10] utilized an exhaustive search by 5-degree intervals for predicting surface roughness in SLS with build height as a secondary objective. The method used the STL file as input and calculated the roughness values for every single facet as the part was rotated about the x- and y-axis. This effort represents one of few deterministic solutions to the orientation problem in AM.

The work of Zhang et al. [25-30] is promising, and the application of feature recognition in non-stochastic optimization schemes for orientation in AM is at this point an unexplored combination – the potential of which is currently unknown.

3. Theoretical background

3.1. The STL file format

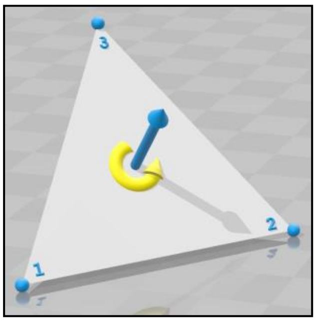
With the first AM technology, a new file format emerged for transferring data for three-dimensional (3D) geometries. The STereoLithography (STL) file format was adopted by other processes as they were introduced, and soon became the de facto industry standard for communicating part geometry in AM [31]. The abbreviation is also described as Standard Triangulation Language or Standard Tessellation Language [32].

As indicated by the more popular abbreviations, the STL file describes a part by a tessellation of triangles constituting the surface of the part. All triangles (facets) are defined by the three coordinates of each corner (vertex), and the unit normal vector of the surface as illustrated in Fig. 1 (left). The file contains a list of all facets with their twelve coordinates as displayed in Fig. 1 (right). The facet unit normal is always pointing outwards, and the vertices are listed in a counter clockwise fashion making the notation of a facet unambiguous [33].

3.2. Feature recognition

Automatic identification of machining features is by no means a new concept, and the literature describes several areas of application [34, 35], however the use of feature recognition in the AM domain is limited. In early research, there are a few occurrences of features being used as a foundation for basic design rules in AM and implicitly considered in orientation [7, 9].

More recently, feature recognition was used in the work of Zhang, et al. [26] who also proposed an alternative facet clustering method as previously mentioned [29, 30]. There are, however currently only stochastic applications of feature recognition to the orientation problem reported in the literature. Feature recognition has the potential to accelerate calculations due to the reduced number of elements compared to all facets of the entire STL-file.



```
solid <name>
  facet normal <x> <y> <z>
    outer loop
      vertex <x> <y> <z>
      vertex <x> <y> <z>
      vertex <x> <y> <z>
    endloop
  endfacet
.....
(Repeats for each facet)
.....
endsolid <name>
```

Fig. 1 Illustration of a triangular facet with normal vector and vertices (left) and the syntax of an STL file in ASCII format (right).

3.3. Surface quality

The surface quality influences not only the physical properties of the part in interaction with its surroundings, but also the visual and haptic perception of the part [36]. Layered manufacturing technologies are prone to the staircase effect inherent in the build process as illustrated in Fig. 2 [2]. Additionally, powder bed fusion processes leave residual particles on the part surface that contributes to increased surface roughness [10]. Finally, processes where support structures are required suffers from poor surface quality in areas where the supports have been removed due to burrs and residue [6]. Water soluble filament for support structures has however been introduced to eliminate this influence in FDM [20].

Of the three influencing factors previously outlined, it is known that part orientation is crucial to control the intensity of the staircase effect [37] and the volume and location of support structures [38]. As supports are redundant in SLS, this paper focus on surface roughness and the staircase effect in particular.

In addition to proper orientation, the staircase effect can also be prevented by reducing the layer thickness [37]. Some AM processes are in fact capable of higher resolution in the z-direction than the x-y plane [39]. Thinner layers will however prolong the build time, and thus methods have been developed for adaptive layer thickness based on the local topography of the part [14]. Adaptive layer thickness can be applied in combination with proper part orientation, but problems arise when multiple parts are manufactured simultaneously as the layer thickness is uniform throughout the build space [40].

While Padhye and Deb [41] predicted surface roughness in SLS based on the orientation of every single facet, the present work utilizes a simplified objective function to facilitate faster computation of optimal orientation. It is however noted that such predictive functions may replace the simple function applied in the present work to incorporate more factors and provide other insights. Such adaptations are however outside the scope of this paper and thus left for future research.

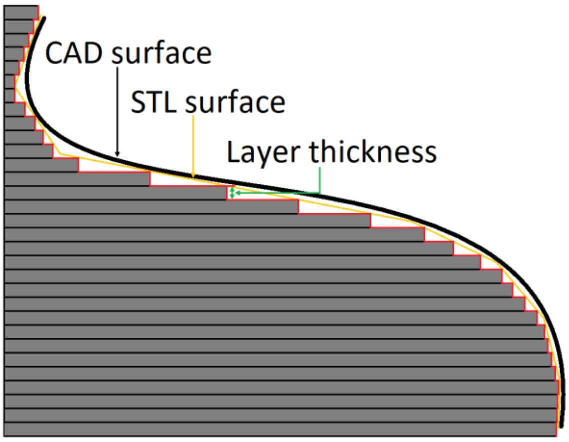


Fig. 3. Illustration of staircase effect and conversion errors.

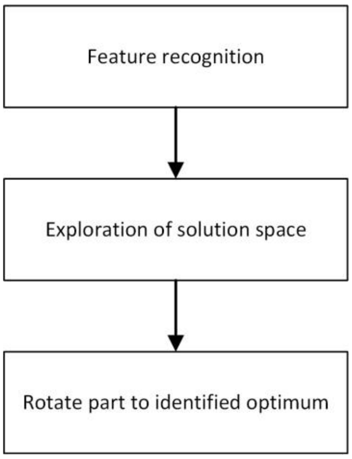


Fig. 2. Flowchart for part orientation.

4. Proposed method

The task of optimizing part orientation is divided in two separate modules as displayed in Fig. 3; the first being feature recognition where geometric features of the STL file are identified, and the second being an exhaustive exploration of the solution space. The objective of the optimization scheme is to find the part build orientation where the staircase effect has the least effect on final surface quality.

In the following it is assumed that every part is made up of a combination of primitive surfaces (plane, cylinder, sphere, cone and torus), and that these features has been successfully extracted from the STL data. This categorization implies that it is possible to represent any freeform surface by a combination of these geometric features. This could however prove to be impractical as the number of features could be tremendous – especially for topologically optimized designs and organic structures. A solution to this challenge could be to disregard freeform surfaces, or to approximate them to one of the basic features.

Furthermore, it is assumed that each feature is accompanied with a vector denoting the orientation of the feature, and that the surface area of the feature is known. Based on this, a function can be designed to evaluate the fitness of different feature types. An exhaustive search for the global optimum is then conducted by rotating the part about the x- and y-axes in increments of one degree. For every increment, a score is aggregated based on the fitness of each feature as

$$S_{tot} = \sum_{i=1} F_i \qquad (1)$$

Where S_{tot} is the aggregated total score for all features in the given orientation, and F is the score of a single feature for the same orientation.

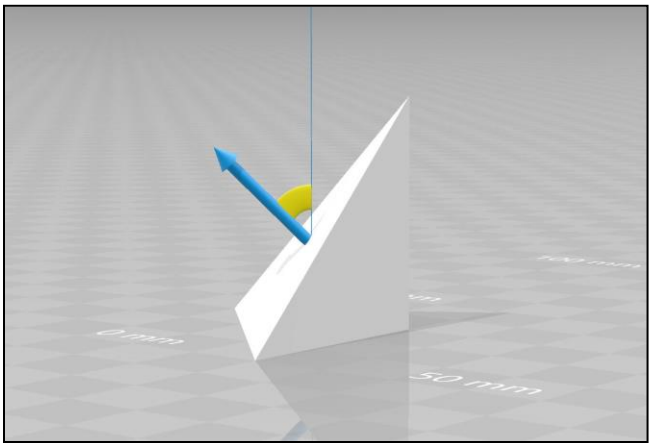


Fig. 4. The angle between the feature normal and the build direction.

The fitness of a given orientation with regards to a specific feature is evaluated as a function of the angle between the feature normal and the build direction as displayed in Fig. 4. Each feature factor should be weighted to prioritize certain features over others. It is here proposed to multiply the fitness factor with the surface area of the feature to give weight to larger features. It is also possible to exclude features smaller than a certain threshold to accelerate computations and avoid the influence of insignificant features.

In the present work, two versions of a simple trigonometric expression is proposed to evaluate the fitness of features with regards to a given orientation:

$$S_{plane} = A \cdot \cos^2\left(2\left(\theta_x + \alpha_x\right)\right) \cdot \cos^2\left(2\left(\theta_y + \alpha_y\right)\right) \quad (2)$$

$$S_{cylinder} = A \cdot \cos^2\left(\theta_x + \alpha_x\right) \cdot \cos^2\left(\theta_y + \alpha_y\right) \quad (3)$$

Where S_{plane} and $S_{cylinder}$ is the score of a plane and a cylinder respectively, A is the surface area of the feature, θ_x and θ_y is the evaluated rotation about the x- and y-axis respectively, and similarly α_x and α_y is the initial offset of the feature about both x- and y- axis.

5. Case study

The method was applied to 19 test parts of varying geometries and origins to investigate the viability of the developed method (see Fig. 5). Three computers were used to eliminate any problems related to a specific unit, and the method was executed three times on each computer to reduce any variability currently present in the computer system. All computers gave identical results considering the proposed solution varying only in execution time.

Table 1 contains a summary of the method's performance on all 19 test parts including the number of recognized features, execution time (in seconds), and qualitative evaluation of end solution. The portrayed performances are the average results of a computer with 8 GB RAM and a 2.30 GHz processor running on 64-bit Windows 10 operating system. No measures (i.e. terminating background processes) were taken to reduce execution time during the trials. The following subsections presents three representative parts (part numbers 2, 6 and 17 of Fig. 5).

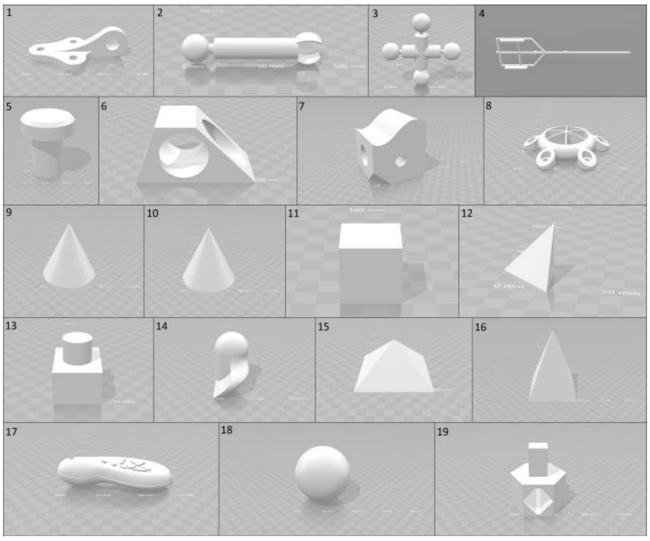


Fig. 5. Overview of all test parts involved in the study.

Table 1. Run time and quality of solutions for 19 test parts.

Part #	Facets	Features	Avg. run time [s]	Quality of solution
1	1 064	9	0.813	Good
2	11 752	96	8.222	Good
3	17 208	77	6.610	Poor
4	7 564	77	6.573	Good
5	900	5	0.414	Good
6	844	9	0.826	Good
7	692	9	0.786	Good
8	59 922	274	23.194	Good
9	70	1	0.088	OK
10	112	1	0.087	OK
11	12	6	0.531	Good
12	4	4	0.331	Good
13	174	7	0.591	Good
14	12 699	326	27.878	Poor
15	6	5	0.410	Good
16	6	5	0.416	Good
17	43 130	905	77.491	Good
18	5 852	5	0.425	N/A
19	80	17	1.405	Good

5.1. Low geometric complexity

Part number 6 is a reconstruction derived from Cheng, et al. [9] where eight distinct features can be identified; six planar sides, and two cylindrical holes. The deviations observed in Table 1 is due to the division of cylinders into multiples, and imprecise data in the STL file.

The method yields a solution where all planar features are oriented either parallel or perpendicular to the build direction thus minimizing the staircase effect on these surfaces. Furthermore, one of the cylindrical holes is oriented parallel to the build direction. This solution is identical to those found in literature [9, 22, 26, 40, 42, 43], thus demonstrating the validity for simple geometries.

5.2. Medium geometric complexity

Part number 2 is a ball joint arm retrieved from literature [44]. The part consists of a cylindrical shaft with a convex sphere on one end, and the concave counterpart on the other. Because the feature recognition module is incapable of recognizing spherical features, both ends of the part is identified as a series of cylinder segments. The effect of this is twofold; (i) the number of features passed on to the orientation algorithm is artificially inflated, and (ii) the dispersed cylinders have contradicting feature vectors that in turn could throw off the orientation algorithm. However, because of the relatively small surface area of the individual segments, the larger features that are correctly identified as cylinders and planes dominates the search.

The proposed solution orients the part parallel to the build orientation minimizing the staircase effect on the large cylinder. The spherical features are not influenced by the build orientation in terms of the staircase effect and can thus be neglected in this assessment.

5.3. High geometric complexity

Part number 17 is a remote control also constructed according to [44]. The part is an assembly of the buttons (all connected in one shell), and the top- and bottom covers. The surface is curved in a free form fashion that introduce significant difficulties for feature recognition resulting in 905 identified features.

Despite the large number of features, the aggregation of many small feature normals of similar orientation makes it possible for the method to propose a valid solution where the remote is oriented in its upright position, with the main surfaces parallel to the build direction. This orientation minimizes the influence of the staircase effect on the largest surfaces, but unavoidably sacrifice some surfaces for the benefit of others.

6. Discussion

The proposed method is developed with an emphasis on consistency and speed. An optimal solution cannot be guaranteed with this method because the accuracy of the results cannot exceed the resolution of the search grid. As the rotational increments are reduced, the execution time grows exponentially and will soon become too time-consuming to be viable. Rotational increments of 1 degree is suggested, but not verified as a neither necessary, nor sufficient interval.

The solutions of the case study is generally believed to be good, but it is clear that the inability of the feature recognition module to identify sphere, cone and torus is a major obstacle for the subsequent search for the optimal orientation. However, it is observed that when features of a certain magnitude are correctly recognized, the validity of the final solution increases dramatically. Proper recognition would however have a major impact on the execution time of the method, which increases linearly with the number of features in the neighborhood of 0.085–0.095 seconds per feature.

The case study demonstrates the method's capability to give stable output given no change in input files. The ability to provide a stable output facilitates standardization and automation, which are key factors in modern industry. With industry 4.0 and mass customization, the need for stable processes may be considered more important than ever. Eliminating variability in complex manufacturing processes facilitates the adoption of AM in industry, and the modernization of manufacturing systems.

There are developments towards direct manufacturing of CAD models without the intermediate STL (or AMF/3MF) file format. Avoiding a tessellated model means increased accuracy because the surface is no longer approximated by triangles. However, such solutions are often application specific and thus generality is lost. The proposed method will in this case become obsolete in its current form, but the concept of utilizing shape features for non-stochastic optimization of orientation in AM remains relevant as this also applies to CAD files.

7. Conclusions

This paper proposed a novel method for optimizing part orientation based on part features without utilizing stochastic techniques. The method will provide the same solution every time given no changes in input, which facilitates automation in industry through elimination of variation. The case study demonstrates the method's feasibility considering execution time and general quality of solutions.

Currently, mitigation of the staircase effect is the sole purpose of the method, and thus the integration of additional objectives is a relevant area of future development, especially objectives contributing to further adaptation by industry such as mechanical properties and accuracy. Furthermore, the algorithm for feature recognition needs to be improved and expanded to handle sphere, cone and torus as these feature types currently may inflict errors in the results.

The developed method is intended for SLS, but the concept can generally be applied to any AM process prone to the staircase effect. An interesting path of future research entails adaptation to other technologies, also outside the powder bed domain.

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