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Build Orientation Determination for Multi-material Deposition Additive Manufacturing with Continuous Fibers

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Abstract

Build orientation of a part in Additive Manufacturing (AM) has complex effect on part's quality, process planning, post-processing, processing time and cost, etc. The identification of the optimal build orientation for a part is one of the main contents of process planning in AM. In this paper, a build orientation optimization strategy is developed for a new AM process, multi-material deposition with continuous fibers, to improve the part quality while reducing the production time & cost. First, a set of finite alternative build orientations are generated by using surface shape feature with associated rules derived from the specific characteristics and constraints of the new developing AM process; then, a multi-attribute decision making algorithm is applied to determine the optimal orientation according to preset preferences. A case study is presented for demonstration.

Keywords: Build Orientation Optimization; Process Planning; Contenuous Fiber; Composite Additive Manufacturing

1. Introduction

Additive Manufacturing (AM) has been developed rapidly in recent years. The application scope and material range are expanding day after day. New AM process and AM integrated process are proposed and implemented by research communities and industries to deal with current challenges and arising new needs in the manufacturing domain [1-8]. Using the AM processing scheme, layer-by-layer material deposition, to fabricate composite parts so as to meet some special requirements in aeronautics application domain, where reinforced and lightweight structures are usually demanded, is a new development direction. A couple of researchers had developed composite materials and related AM processes to fabricate reinforced parts [9-12]. There are two main groups of methods for composite AM, one is direct composite AM which can build composite parts directly and the other is indirect composite AM that is used by providing soluble core materials to facilitate the fabrication of complex composite parts for traditional processing technologies [12]. In this paper, the scope is direct composite AM via fused deposition modeling (FDM). The major drawback of producing composite parts via FDM is the need to produce a reinforced polymer filament compatible with existing FDM equipment, which is not a trivial task [12]. Most of the current research practice in this direction is to develop new materials with short fibers mixed for reinforcement. However, the fabricated composite parts have different properties to traditional composite parts and the fibers are not continuous. In addition, those developed new materials are usually not compatible with current FDM machines. To solve these problems, a new direct composite AM process, multi-material deposition reinforced with continuous carbon fiber, is proposed and under development. In the first development stage, a 3-axis FDM experimental platform, which will be introduced later in this paper, had been constructed to build 3D parts with fully continuous carbon fibers for reinforcement. For 3-axis AM processes, also called flat-layer concept AM processes, there are mainly two directions to optimize the build procedure for a given part, one is optimizing layer filling pattern (tool-path planning) and the other is optimizing the build direction (orientation optimization). To optimize the part quality when using this process, there is a need of an orientation optimization method. However, due to the special processing characteristics of this new FDM process, current orientation optimization methods in literature can't be directly adopted. Hence, this paper is dedicated to propose an orientation optimization method for the new FDM process.

The structure of this paper is organized as follows: the second section will review current orientation optimization methods in literature; the third section will introduce the newly developed FDM platform with its specific processing characteristics and constraints; the fourth section will present the proposed customized orientation optimization method; the fifth section will present a demonstration and the last section will conclude the research with some perspectives.

2. Orientation optimization methods in literature

Build orientation, as one of the preparation or process planning steps in AM, is very important to the production result since it affects the downstream preparation procedures, such as support generation, slicing, tool-path generation, etc., which co-determine the final build time, cost and quality. Due to the importance, many researchers have investigated this problem for a long time. To solve this problem, there are two main tasks [13], one is identifying a set of alternative orientations from an infinite alternative build orientation space for a 3D part since it can rotate freely around three axes with infinite angle options in the 3D build space, and the other is to apply multi-criteria decision making method for determining the optimal out of the pre-identified alternatives. To solve the first task, there main two groups of methods, rule or knowledge based method and sampling method or listing method. For the rule or knowledge based method, base planes, key surface features or user-defined surface features on a 3D part model are used with associated rules to suggest a set of finite alternative build orientations [14-19]. For the sampling or listing method, a mathematical or statistical method was used to explore a predefined smaller orientation space from the theoretically infinite solution space [20-23]. Genetic algorithm and RSM (response surface methodology) are the two representatives. To deal with the second task, multi-criteria were usually defined to be considered in order or simultaneously through the applying of suitable decision algorithms. Since the build orientation affects many downstream processing chains, usually a group of factors with complex interrelations should be considered. When adopting a sampling or listing method with mathematical or genetic algorithms to do the optimization, the computation is very costly as the searching step length decreases. When considering multiple factors or criteria simultaneously, the computation becomes more complex due to the additional computation for multi-objective functions. Hence, this kind method is not efficient to solve the first task [23]. While rule or knowledge based method is more effective to identify a set of finite alternative orientations since it can focus on more practical alternative orientations and implicitly capture the embedded design intention when a part is designed for the process. Hence, to save computation time and to simplify the orientation problem of the new composite AM, this paper uses a feature and rule-based method to generate finite alternative orientation set and a multi-attribute decision making model is applied. However, due to the special processing characteristics and constraints of the new composite AM, the former method cannot directly be adopted but needs to be adapted. To conduct effective optimization for any engineering problem, the specific characteristics and constraints of the particular technology under investigation should be firstly considered [24]. Therefore, there is a need to deeply analyze the new FDM process so as to develop a customized orientation optimization method.

3. Processing characteristics of the new composite AM

As a platform to experimentally prove the developed new composite AM, an industrial 6 degree of freedom KUKA KR6 R700 robot is modified and supplied with a heated bed end effector as shown in Fig. 1. Currently, the build bed can translate through 3 axes to make this platform function as a 3-axis 3D printer. Multiple nozzles are mounted to an overhang frame to extrude multiple materials, including support material and part materials, bonding plastic and carbon fibers.

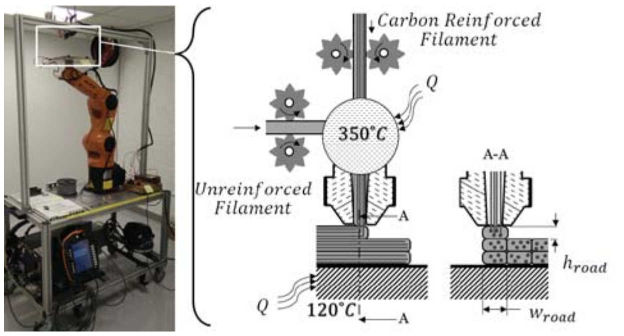

Fig. 1. The new composite AM experimental setup and mechanism

A special 3D printer nozzle designed and dedicated to print continuously reinforced carbon fiber filament is used. This setup allows reinforcement with carbon fibers not only in plane, but also out of plane since continuous fibers can jump from one layer onto the next adjacent layer without cutting if the tool-path is well-planned. In-plane reinforcements with carbon fiber, a concept similarly proven by the team of the Markforged Mark one printer [25], have proven to result in a specific flexural modulus higher than 6061T6 Aluminum. The interlaminar strength can be increased by printing in the build direction, and additionally boosts up this interlaminar strength through the addition of carbon fibers. The current capabilities of the system have only been proven in a standard XYZ configuration, which allows for standard layer-by-layer specimen to be printed. An example of a continuous carbon fiber reinforced 3D printed specimen is shown in Fig. 2. To print continuous carbon fiber reinforced of parts, a very similar approach is used to the standard FDM printing process except the extrusion of fibers with fused bonding plastics. Uniform slicing is used to adapt for the current 3-axis FDM composite AM experimental platform.

Fig. 2. Sample print produced by the new developing process [26]

Since the loaded fiber diameter is usually fixed and will not be fused during the deposition process, some special processing characteristics related with build orientation turn up for this composite AM.

- ***Layer thickness and deposition road width are fixed***. Since the fiber is fused during the deposition, the layer thickness and road width are, in part, determined by the fiber diameter and the fixed extruded fused bonding materials, which are constant for this setup.
- ***A minimum corner radius should be maintained***. When the polymer around the carbon fibers in the product solidifies, the resulting the deposition has an increased stiffness with respect to unreinforced depositions due to the presence of the carbon fiber. Therefore, downstream effects such as delaminations may occur when a sharp corner is made. Additionally, sharp corners can cause fiber shearing which may result in fiber breakage. Hence, for each slice, a minimum corner radius on the slice profile and tool-path should be maintained so as to guarantee the manufacturability.
- ***Fiber cutting is required when changing deposition area or treating a slice with sharp corner***. Fibers have to be cut when printing with continuous fibers for disconnected areas and profiles with sharp corners within a slice or jump between two slices without overlapped end and starting deposition points. The cutting takes a certain amount of time as the bed feed has to be stopped, the unused extruded fiber has to be cut and removed from the system. The feed also has to be restarted at the start of a new deposition segment, which also requires a time interval.

The three mentioned processing features of the new composite AM are different to other FDM process and they are affected by the build orientation with other related dowstream preprocessing chains, e.g. slicing. Therefore, when conducting build orientation optimization for this composite AM, alternative orientation generation rules and decision making related factors or criteria, which are related with these processing characteristics should be considered. The next section will present a modified rule-based orientation optimization strategy with respect to the special characteristics above.

4. Proposed orientation optimization method

In this paper, a feature and rule-based method, composed of two main steps, is adopted from [18, 19] and modified to fit the new process. In the first step, a decomposition operation is conducted to divide a surface 3D STL model into a couple of pre-defined surface shape feature units. Then, pre-defined rules are used to generate a set of alternative build orientations for each obtained surface shape feature units. After that, these sets of alternative orientations are refined and used as alternatives for the original 3D STL model. In the second step, a list of decision or evaluation criteria are defined according to the processing characteristics and constraints of the new composite AM. Then, a decision model is applied to support the decision making while selecting the optimal build orientation from the pre-defined alternative orientation list. The flowchart of this method is given by Fig. 3.

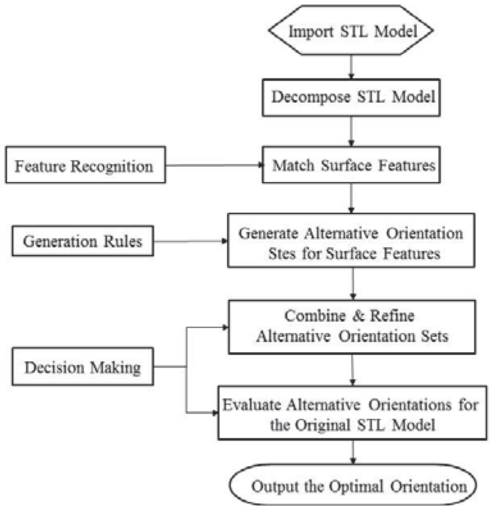

Fig. 3. Orientation Optimization Method

4.1 Alternative Orientation Generation Method

In this paper, three main types of basic shape feature units, cylindrical shape, planar shape and tapered shape, are defined and related alternative orientation generation rules are defined according to the special processing characteristics and constraints of the new composite AM (Fig. 4). Each defined rule is used to generate a set of finite alternative build orientations which are beneficial for its associated shape feature unit.

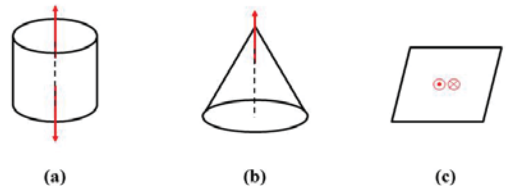

Fig. 4. Generation rules for three shape feature unit types (arrows indicate alternative build orientations)

For cylindrical type, the build orientation should be parallel to the shaft to facilitate the depositing of continuous fibers in a contouring way without cutting within each slice and the jumping to the next layer directly without cutting the fibers. For the tapered type, there is only one optimal build orientation which is parallel to its center axis. This build orientation facilitates the continuous fiber deposition, jumping without cutting to adjacent layers and does not need support structures. For the planar type (including planar shapes with irregular polygon boundary), the build orientation should be perpendicular to the plane where the planar shape is on, which is helpful to the contouring deposition and reduce the total number sharp corners where fiber cuttings are required. If the build orientation is parallel to the planar surface, there is a need of a “U” turn between two slices, which usually forms a sharp corner near the shape profiles. As introduced before, a STL surface model can be decomposed into a set of defined shape feature units, complete shapes or incomplete shapes, and apply orientation generation rules for these shape units to generate a set of finite alternative build orientations, which are taken as alternative build orientations for the original STL model after refining, removing duplicates and combining very similar orientations. The angle between two alternative orientations is used to do the refining. An alternative orientation with an angle value dropping into the range of [0, 5] degrees will be treated as a duplicate or a very similar build orientation. To identify the optimal build orientation for the original STL model, decision making criteria and model should be applied. The next sub-sections will introduce this.

4.2 Decision Criteria and Model

Build orientation optimization problem is a typical multi-criteria decision making problem due to the complex affecting factors. It is difficult to consider all the potential factors without bias. Hence, it is practical to identify the most important factors for a target AM process as decision criteria. Based on this point, this paper identifies four main decision criteria, two special criteria and two general criteria.

- ***Minimum total sharp corners of all slices***

Since a minimum corner radius for the continuous fiber deposition should be maintained, the total sharp corners for a sliced STL model should be minimized. Additional cutting operations, which need more build time, should be conducted to fill the narrow areas with sharp corners (Fig. 5).

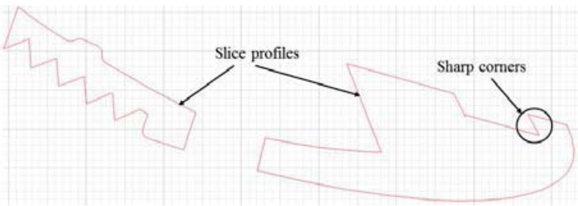

Fig. 5. A slice with disconnected deposition areas and sharp corners

Sharp corners also cause problems of void area, overlaps in narrow deposition areas, difficulty for tool-path planning, etc. Build orientation affects the slicing result since different orientations will have different slice profiles when applying uniformed slicing. Hence, an optimal build orientation should have the minimum total sharp corners. The calculation of number of corners is as follows: for each set of consecutive deposition segments j and $j+1$, described by vectors $\boldsymbol{D}_j$, and $\boldsymbol{D}_{j+1}$, if the angle between the unit vectors describing the direction of these depositions $\boldsymbol{U}_j$ and $\boldsymbol{U}_{j+1}$, is larger than a pre-set value θ_{max}, then a corner is detected and added to a local count. The sum of all these corners is then the total model corner count. If one or both of the segments of two consecutive segments is travel (defined as movement without extrusion), this angle does not count as a corner, and the case is excluded from the count. The angle between the two depositions can be found using the dot product of the two unit vectors. The mathematical description for the identification of corners thus becomes:

$$\overline{U}_j \cdot \overline{U}_{j+1} > \cos\theta_{\max} \quad (1)$$

Large surfaces parallel with the build direction will contain infill, which may create a high corner count. Ideally, infill is not present when printing with these materials. Therefore, only a shell-like structure was considered for the example in the following sections. For the calculations in this paper, $\boldsymbol{\theta}_{max}$ was set as 45 degrees.

- ***Minimum total cutting numbers of fibers***

As discussed previously, cutting operations are usually required when dealing with sharp corners, switching deposition from one area to another disconnected area within a slice and jumping from one finished layer to the next layer if the tool-paths of two layers are not connected. Build orientation affects the slicing result and the total numbers of disconnected deposition areas of slices. Therefore, an optimal build orientation should be the one that has the minim number of disconnected deposition areas. This means a minimum total number of cuttings can be obtained. Slice information is used for calculating the total number of cuttings for a given alternative build orientation by counting the number of extrusion parameter changes, which derive from switching to different deposition areas and filling the sharp corners.

- ***Minimum Z-size-error***

Different build orientations have different build heights. Usually, a minimum Z-height will result to a minimum build time. However, for FDM process, Z-height is not the main time factor since the time fraction for the movement of nozzles is trivial compared to the time for cleaning nozzles and loading filaments. In this new composition AM, Z-height is also not a key factor. But, due to the fixed layer thickness and fiber diameter of this process, there is a problem of Z-size-error when the build height is not an integer times of the layer thickness (Fig. 6). Hence, an optimal build orientation should have a minimum Z-size-error. A formula for representing the Z-height-error of an alternative build orientation is given as:

$$\boldsymbol{E_z} = \left[\boldsymbol{1} - \left(\frac{\boldsymbol{Z}}{\boldsymbol{h}} - \left\lfloor\frac{\boldsymbol{Z}}{\boldsymbol{h}}\right\rfloor\right)\right]^{\boldsymbol{2}} \quad (2)$$

, where $\boldsymbol{E_z}$ is Z-height-error, $\boldsymbol{Z}$ is the build height and $\boldsymbol{h}$ is the layer thickness.

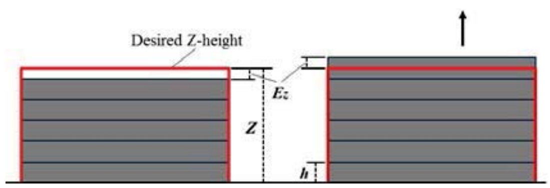

Fig. 6. Z-size-error in fixed fiber layer deposition

- ***Minimum support volume***

This is a general decision criterion for many AM processes where support structures are required to provide force for overhanging down surface areas. In this composite AM, soluble support structures are also required to support overhanging structures and inner hollow structures. The support volume calculation method proposed by [27] is adopted here to predict the soluble material volume used for each alternative build orientation in an approximate way.

Certainly, apart from these criteria discussed above, there are also other direct or indirect general orientation factors that could be considered as decision criteria, such as surface roughness, etc. However, for the new process, these four identified criteria are more important to the manufacturability and final production time and cost. To conduct multi-criteria decision making, a decision model is required. There are many multi-decision making models proposed in literature. Different models have different pros and cons. In this paper, to handle the unclear interrelations among selected decision criteria, an integrated decision making model [28-29] which has two measuring metrics: ‘distance’ and ‘similarity’, is used. Due to limited space in this paper, details about this decision model are not presented here. Interested readers are advised to consult more information in the references.

5. Case study

In this section, the determination of the optimal build orientation for a thin wall STL model to be built by this new composite AM process is used as an illustrative example to show the procedures of the proposed method. In the first step, the STL model is decomposed into a set of basic surface shape features, including 3 cylindrical features, 1 tapered feature and 9 planar features. By analyzing the decomposed surface shapes and the symmetrical properties, only 8 features are identified (Fig. 7). A feature recognition method is based on the facets’ normal and curvature information. More details can be found in [30].

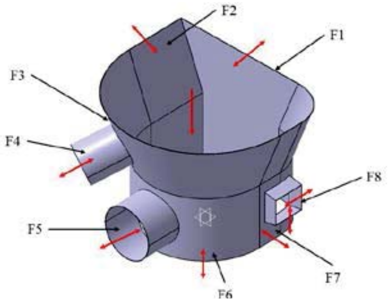

Fig. 7. Shape features and build orientations for a thin wall part model

Then, the pre-defined alternative orientation generation rules are applied to these surface features to generate alternative build orientations (red arrows in Fig. 7). After removing duplicates, 8 alternative build orientations are generated for the original STL model as shown in Fig. 8.

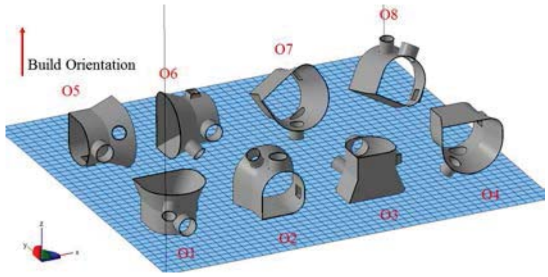

Fig. 8. Refined alternative orientations for the STL model

In the second step, the pre-identified four decision criteria are used to evaluate each of the alternative build orientations. The STL model is rotated to each of the alternative orientations and sliced with a thickness of 0.25 ***mm*** in a uniformed way to calculate the total number of sharp corners, fiber cuts, Z-size-error and support volume. The prediction calculation results are presented in Table 1.

Table 1. Prediction values of alternative build orientations.

Orientation	No. Cutting	No. Corner	Z-size-error	Support Volume/*mm* (*length of support material*)
O1	3137	3982	0	990
O2	2557	2894	0.0576	200
O3	3177	3344	0	540
O4	2531	3070	0.0576	7340
O5	3515	5223	0	4830
O6	3520	5243	0	3930
O7	3204	2524	0.9216	6560
O8	3110	3032	0.9216	9580

With these prediction values in hand, the multi-criteria evaluation for the alternative orientations can be conducted. As introduced in Section 4.3, the integrated model is adopted for decision making. In this example, the weights are evenly assigned to each of the four criteria. After computation, the decision results are obtained and depicted in Table 2. The alternative orientation, ***O3***, ranked highest and is identified as the optimal build orientation for the STL model.

Table 2. Decision results.

Orientation	Decision Value	Ranking
O1	0.9869	2
O2	0.9837	3
O3	0.9937	1
O4	0.8852	6
O5	0.9322	5
O6	0.9446	4
O7	0.6578	7
O8	0.6158	8

To obtain more reliable optimization results, more decision criteria can be taken into consideration and more accurate and reasonable weight assignment can be applied according to real application and user preferences. Though the computation cost can be reduced by using a feature and rule-based orientation method, the global optimal cannot be guaranteed. To improve the optimization and save computational effort, this method can be combined with other computational methods, e.g. Genetic Algorithms. The alternative build orientations generated by using this proposed method can be used as local searching base for listing computational method. Genetic algorithm can be used to explore the solution space near each searching base, alternative orientation, by slightly rotating the alternative orientation so as to find better solution. Future work will be done to aid in the development of this kind of hybrid orientation optimization method.

6. Conclusion

A modified feature and rule-based orientation optimization method for a new developing composite AM process is proposed. New key orientation factors were identified according to the special processing characteristics and constraints. The proposed method with those identified new decision criteria will be used as a base for developing more advanced process planning algorithms for the new composite AM in the future. In addition, they can also be structured and used to guide the design for this new composite AM. New design rules and methods for this process will be developed based on this research in the near future.

Acknowledgements

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References

[1] Kruth, J. P., Leu, M. C., & Nakagawa, T. (1998). Progress in additive manufacturing and rapid prototyping. CIRP Annals-Manufacturing Technology, 47(2), 525-540.

[2] Bernard, A. & Fischer, A. (2002). New Trends in Rapid Product Development, 51(2), 635-652.

[2] Mohri, N., Takezawa, H., Furutani, K., Ito, Y., & Sata, T. (2000). A new process of additive and removal machining by EDM with a thin electrode. CIRP Annals-Manufacturing Technology, 49(1), 123-126.

[3] Zhang, H., Xu, J., & Wang, G. (2003). Fundamental study on plasma deposition manufacturing. Surface and Coatings Technology, 171(1), 112-118.

[4] Janaki Ram, G. D., Robinson, C., Yang, Y., & Stucker, B. E. (2007). Use of ultrasonic consolidation for fabrication of multi-material structures. Rapid Prototyping Journal, 13(4), 226-235.

[5] Yves-Christian, H., Jan, W., Wilhelm, M., Konrad, W., & Reinhart, P. (2010). Net shaped high performance oxide ceramic parts by selective laser melting. Physics Procedia, 5, 587-594.

[6] Karunakaran, K. P., Suryakumar, S., Pushpa, V., & Akula, S. (2010). Low cost integration of additive and subtractive processes for hybrid layered manufacturing. Robotics and Computer-Integrated Manufacturing, 26(5), 490-499.

[7] Melchels, F. P., Domingos, M. A., Klein, T. J., Malda, J., Bartolo, P. J., & Hutmacher, D. W. (2012). Additive manufacturing of tissues and organs. Progress in Polymer Science, 37(8), 1079-1104.

[8] Zhong, W., Li, F., Zhang, Z., Song, L., & Li, Z. (2001). Short fiber reinforced composites for fused deposition modeling. Materials Science and Engineering: A, 301(2), 125-130.

[9] Karalekas, D., & Antoniou, K. (2004). Composite rapid prototyping: overcoming the drawback of poor mechanical properties. Journal of materials processing technology, 153, 526-530.

[10] Kumar, S., & Kruth, J. P. (2010). Composites by rapid prototyping technology.Materials & Design, 31(2), 850-856.

[11] Cerneels, J., Voet, A., Ivens, J., & Kruth, J. P. (2013). Additive manufacturing of thermoplastic composites. Composites Week@ Leuven, 1-7.

[12] Kulkarni, P., Marsan, A., & D.Dutta, D. (2000). A review of process planning techniques in layered manufacturing. Rapid Prototyping Journal, 6(1), 18–35.

[13] Frank, D., & Fadel, G. (1995). Expert system-based selection of the preferred direction of build for rapid prototyping processes. Journal of Intelligent Manufacturing, 6(5), 339-345.

[14] Pham, D. T., Dimov, S. S., & Gault, R. S. (1999). Part orientation in stereolithography. The International Journal of Advanced Manufacturing Technology, 15(9), 674-682.

[15] West, A. P., Sambu, S. P., & Rosen, D. W. (2001). A process planning method for improving build performance in stereolithography. Computer-Aided Design, 33(1), 65-79.

[16] Byun, H. S., & Lee, K. H. (2006). Determination of the optimal build direction for different rapid prototyping processes using multi-criterion decision making. Robotics and Computer-Integrated Manufacturing, 22(1), 69-80.

[17] Zhang, Y., & Bernard, A. (2013, October). Using AM feature and Multi-attribute decision making to orientate part in additive manufacturing. In High value manufacturing: Advanced research in virtual and rapid prototyping. Proceedings of the 6th International Conference on Advanced Research in Virtual and Rapid Prototyping (pp. 411-416).

[18] Zhang, Y. Bernard, A., Gupta, R., & Harik, R. (2016). Feature Based Building Orientation Optimization for Additive Manufacturing. Rapid Prototyping Journal, (in press).

[19] Cheng, W., Fuh, J. Y. H., Nee, A. Y. C., Wong, Y. S., Loh, H. T., & Miyazawa, T. (1995). Multi-objective optimization of part-building orientation in stereolithography. Rapid Prototyping Journal, 1(4), 12-23.

[20] Xu, F., Loh, H. T., & Wong, Y. S. (1999). Considerations and selection of optimal orientation for different rapid prototyping systems. Rapid Prototyping Journal, 5(2), 54-60.

[21] Masood, S. H., Rattanawong, W., & Iovenitti, P. (2003). A generic algorithm for a best part orientation system for complex parts in rapid prototyping. Journal of materials processing technology, 139(1), 110-116.

[22] Padhye, N., & Deb, K. (2011). Multi-objective optimisation and multi-criteria decision making in SLS using evolutionary approaches. Rapid Prototyping Journal, 17(6), 458-478.

[23] Canellidis, V., Giannatsis, J., & Dedoussis, V. (2013). Efficient parts nesting schemes for improving stereolithography utilization. Computer-Aided Design, 45(5), 875-886.

[24] https://markforged.com/mark-one/.

[25] Antonov, F. & Azarov, A. (2016) Anisoprint, “Revolutionary 3D Printing Technology”, www.anisoprint.com, Accessed February 13, 2016

[26] Chen, Yong, and Rajeev Kulkarni. "Support volume calculation for a CAD model." U.S. Patent Application No. 10/461,957.

[27] Zhang, Y., & Bernard, A. (2014). An integrated decision-making model for multi-attributes decision-making (MADM) problems in additive manufacturing process planning. Rapid Prototyping Journal, 20(5), 377-389.

[28] Zhang, Y., Bernard, A., Harik, R. & Karunakaran, K.P. (2015). Build orientation optimization for multi-part production in additive manufacturing. Journal of Intelligent Manufacturing, pp 1-15, in press.

[30] Moroni, G., Syam, W. P., & Petrò, S. (2015). Functionality-based part orientation for additive manufacturing. Procedia CIRP, 36, 217-222.