View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by CiteSeerX

Proceedings of the ASME 2010 International Design Engineering Technical Conferences &
Computers and Information in Engineering Conference
IDETC/CIE 2010
August 15-18, 2010, Montreal, Quebec, Canada

DETC2010-28440

2-D PATH PLANNING FOR DIRECT LASER DEPOSITION PROCESS

Swathi Routhu — Department of Computer Science
Divya Kanakanala — Department of Computer Science
Jianzhong Ruan — Product Innovation and Engineering LLC
Xiaoqing Frank Liu — Department of Computer Science
Frank Liou — Department of Mechanical and Aerospace Engineering

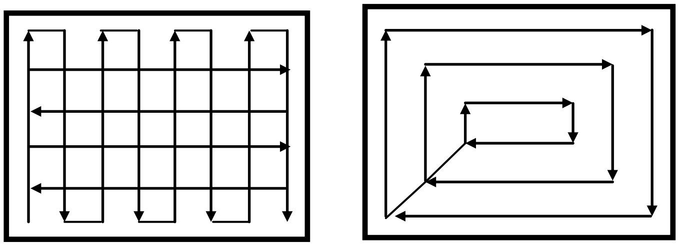
Missouri University of Science and Technology
Rolla, MO, 65401

ABSTRACT

The zigzag and offset path have been the two most popular path patterns for tool movement in machining process. Different from the traditional machining processes, the quality of parts produced by the metal deposition process is much more dependent upon the choice of deposition paths. Due to the nature of the metal deposition processes, various tool path patterns not only change the efficiency but also affect the deposition height, a critical quality for metal deposition process. This paper presents the research conducted on calculating zigzag pattern to improve efficiency by minimizing the idle path. The deposition height is highly dependent on the laser scanning speed. The paper also discussed the deposition offset pattern calculation to reduce the height variation by adjusting the tool-path to achieve a constant scanning speed. The results show the improvement on both efficiency and height.

1. INTRODUCTION

Since its appearance in 80s of last century, Layered Manufacturing (LM) technology, also known as Rapid Prototyping (RP) has given industry an approach to achieve the goal of providing products with a shorter development time and a lower cost. It involves successively adding raw material, in layers, to create a solid part directly from a CAD model instead of removing material as in the traditional subtractive manufacturing processes such as machining. LM processes fabricate a physical part in an additive fashion, layer by layer. The metal rapid prototyping process is a potential technique that can produce fully functional parts directly from a CAD system and eliminate the need for an intermediate step. Among LM processes, direct laser deposition process is capable to fabricate fully dense metal parts directly from the CAD model. Such a process has drawn interest from aerospace, heavy machinery and other industries.



(a) Zigzag path (b) Offset path

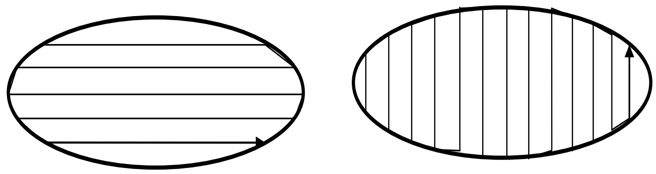
FIGURE 1: ZIGZAG AND OFFSET PATH

Due to its complexity, such a process requires an automatic planning system to drive. Automatic deposition path planning is a critical component in the planning system. The current common practice is to use commercial available machining CAD/CAM package or other specific planning systems to generate 2-D deposition path. However, the results obtained from these planning systems cannot meet all needs for metal deposition processes. Material additive process features needed to be considered when generating deposition path. The typical 2-D path patterns are raster pattern which is also called zigzag path (Figure 1.a) and spiral-like or offset path (Figure 1.b) pattern. Each of them has its own advantages and can be used to generate deposition path. Systems built on this principle include LENS [1], DMD [2].

This paper presents the study of the usage of different 2-D deposition patterns. The zigzag path is generated to improve the efficiency by reducing the idle or non-deposition path.

Copyright © 2010 by ASME

Downloaded From: https://proceedings.asmedigitalcollection.asme.org on 06/27/2019 Terms of Use: http://www.asme.org/about-asme/terms-of-use



(a) 0° Inclination: Five tool-path elements (b) 90° Inclination: Thirteen tool-path elements

FIGURE 2: INCLINATION AND THE NUMBER OF TOOL-PATH ELEMENTS

Different from the machining process, the deposition height is highly determined by the scanning speed given a constant laser power and material feeding rate. Using this characteristic, the offset path is generated and optimized to minimize the variation of the scanning speed to maintain the deposition height estimation. This paper is organized as follows: in the next section, the related work is summarized. The metal deposition process is briefly discussed in section 3. The zigzag and offset tool-path generation and optimization are presented in section 4. The general algorithm, with some examples, is illustrated in section 5. The paper is concluded in section 6.

2. RELATED WORK

In layered manufacturing, the quality of the parts is still very much dependent upon the shape of the deposition paths [3], especially for direct metal deposition processes. Even though the deposition path patterns have been studied for a long time, including raster path, contour offsetting paths and spiral-like offsetting paths etc, there are still some problems or assumptions associated with different algorithms.

In the zigzag pattern, the tip of the nozzle is moved back and forth parallel to referenced directions. The common zigzag pattern technique is to scan in the direction parallel to the longest side of the geometry results in the shortest deposition path. However, the angles of the zigzag paths are still the source of localized build errors which cause the unevenness aligned with the direction of paths in the build [3]. A zigzag pattern which is based on the optimal inclination of the tool and the tool path elements in the specific inclination and connecting the tool path elements to form a shortest path in the milling process is explained [4], illustrated in Figure 2.

In an offset pattern, offset segments of the geometry boundaries are generated and used as a guide for the nozzle to move along. By tracing the offset paths, residual stress could be relieved before tracing the next adjacent edges. Therefore, stress-induced warping is reduced. This pattern includes pair-wise offset, pixel-based offset, Voronoi approaches and spiral-like offset. However, these approaches usually have some problems such as detecting the intersection of offset edges and removing invalid loops [5~7] and being computationally intensive [8] and numerically stable [9, 10]. Based on the work performed by Kao and Prinz [3], spiral offset paths are typically preferred for producing isotropic deposits. In [11], a modified approach to generate offsetting edges is introduced. This algorithm divides the deposition layer into some unconnected regions for which the offsetting paths will be generated for every single region component. Apparently, this method has more power to handle some complicated arbitrary shapes, especially those with inner loops. On the other hand, these tool-path generation methods do not consider the path effect on the scanning speed. The fabrication resolution can be improved by adjusting the power level [12]. Adjusting the offset tool-path to achieve a constant cutting force has been studied by Wang et al. [13]. Both of them have considered the effect of power and tool-path on the results. A similar concept has been developed for metal deposition process to reduce the variation of the deposition height.

In this paper, a zigzag path generation is developed based on the hierarchy structures of a shape. A shape is divided into several sub-areas which are formed as a hierarchy graph structure. The path connection problem is converted into "travelling salesman" problem. For offset pattern generation, the deposition height model is developed and relationship between the path and scanning speed model is used to optimize deposition path.

3. POWDER-BASED LASER METAL DEPOSITION PROCESS

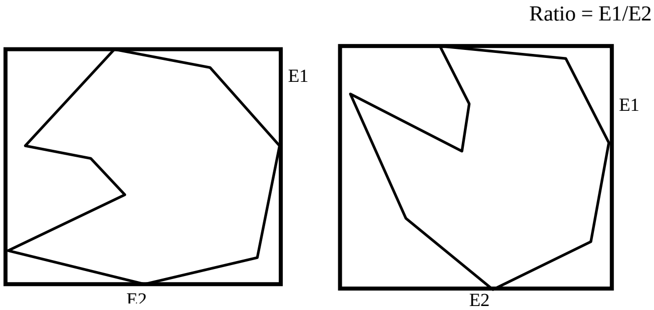
Usually, a laser powder-based metal deposition process consists of a high power laser, powder delivery system, cladding nozzle, and motion control. In a typical laser powder-based metal deposition process, powder is injected into the melt pool and then solidified to form the geometry. Different than other rapid prototyping processes, there is overlap between each track. Some unmelted powder during one track deposition is melted when the laser scans the neighboring area and this effect may cause the uneven layer height deposition. To investigate this effect, experiments have been run using different laser scanning patterns in the Laser Aided Manufacturing Process (LAMP) lab at Missouri University of Science and Technology (Missouri S&T). LAMP's process is a multi-axis hybrid manufacturing process which can directly produce functional parts with machining accuracy [14]. The diode laser in the LAMP lab is used in this research to achieve better energy efficiency.

4. 2-D PATH PLANNING

2-D deposition pattern and strategy study has been investigated and the zigzag and offset pattern is selected for each sub-region based on geometric shape [15]. The two different tool-path generations are discussed below.

Copyright © 2010 by ASME

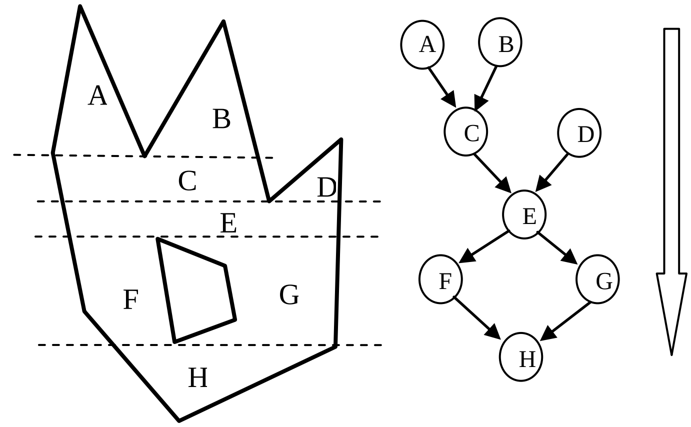
Downloaded From: https://proceedings.asmedigitalcollection.asme.org on 06/27/2019 Terms of Use: http://www.asme.org/about-asme/terms-of-use



(a) Bounding box with larger ratio

(b) Bounding box with smaller ratio

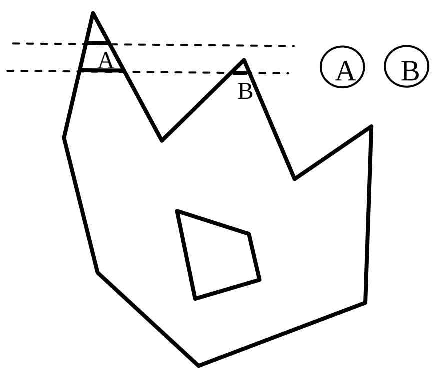
FIGURE 3: BOUNDING BOXES WITH DIFFERENT RATIO



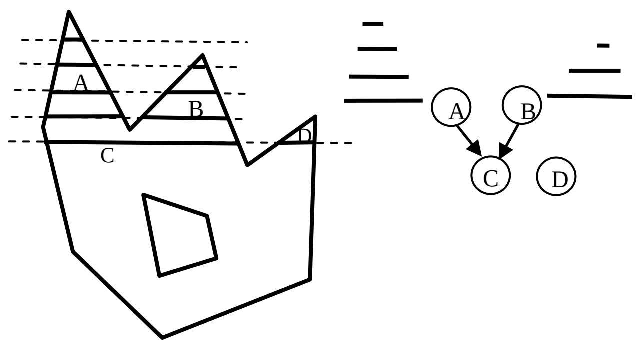
(a) Zigzag path regions

(b) The Graph structure

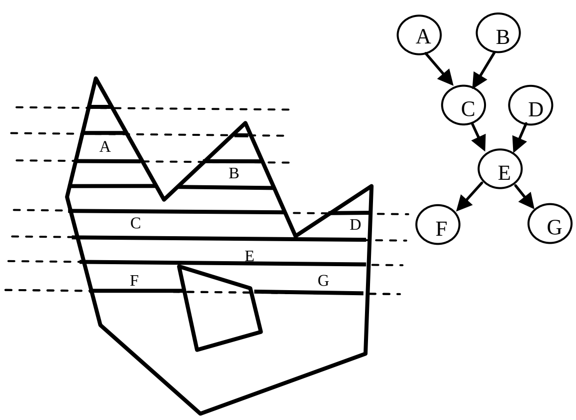
FIGURE 4: HIERARCHY GRAPH STRUCTURE



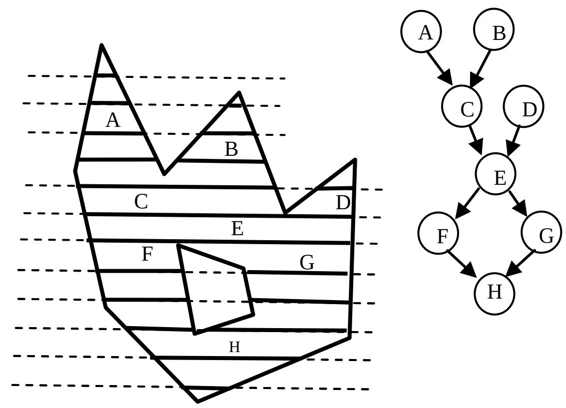
(a) The first two nodes are A and B



(b) A and B are complete due to the topological change. Node C and D are created. Node A and B are parents of Node C



(c) The graph is continuously formed



(d) The final graph

FIGURE 5: HIERARCHY GRAPH FORMATION USING ZIGZAG PATH

4.1 2-D Zigzag Path Planning

A typical zigzag path consists of a number of parallel segments. The path travel direction and connection determines the efficiency. Path orientation determines the entire path length. In laser deposition process, the “idle” or non-working path should be as short as possible due to the energy consumption and potential material waste. Path connection determines the length of “idle” paths; thus, the tool-path orientation and path connection are two critical techniques in generating zigzag path.

4.1.1 The tool-path direction determination

Copyright © 2010 by ASME

Downloaded From: https://proceedings.asmedigitalcollection.asme.org on 06/27/2019 Terms of Use: http://www.asme.org/about-asme/terms-of-use

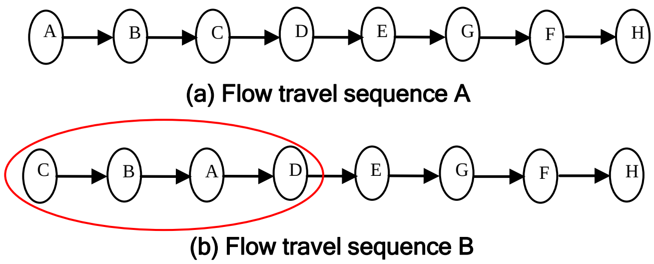


FIGURE 6: ZIGZAG PATH TRAVEL SEQUENCE

Illustrated in Figure 2, it can be observed that the tool-path with an inclination of 90° is having more number of non-depositing track paths compared to the one with 0° inclination. Also the total length of 90 ° is longer than the path of 0° inclination. In this research, the bounding box concept is

used to select the inclination direction for zigzag path instead of using the longest edge of a 2-D shape. The ratio of the longer edge to shorter edge of the bounding box is different, as shown in Figure 3 and it is used to determine the inclination direction. In this research, the bounding box with the largest ratio is used to generate zigzag path. In order to find the bounding box with the largest ratio for a 2-D shape, the shape is rotated and the bounding box at each orientation is obtained.

4.1.2 Graph structure Construction

Once the zigzag path orientation is determined, a series of parallel paths can be generated. Connecting these paths has many different ways which results in the difference in efficiency. A hierarchy graph is designed for zigzag paths and is used as guide for path connection, illustrated in Figure 4. Such a hierarchy structure is formed while generating the zigzag path as shown in Figure 5. When the first parallel is obtained, node (s) is (are) created for each segment. Each node contains a series of parallel segments, as shown in Figure 5 (a). When topological relationship changes, the current node is complete and another new node is created to record the newly generated tool-path. A "parent-child" relationship is formed between these two nodes.

The hierarchy graph not only defines the different areas (regions) of a 2-D shape following the zigzag orientation but also defines the path connection sequences. In this hierarchy graph, the level is assign to each node. The parents of the same child are assigned as the same level. In the graph shown in Figure 4, Node A and B are on the same level; Node C and D are on the same level and the level assignment can be established using this method. Using breath searching technique to travel the hierarchy graph, a travel sequence can be clearly obtained. In order to avoid unnecessary "back and forth" movement, the left top point is taken as the starting points. Shown in Figure 6, it is very clear that the sequence A is more efficient than the sequence B since the "jump"

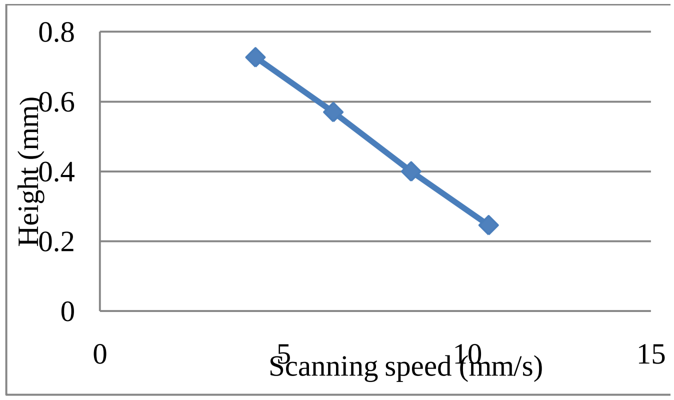


FIGURE 7: EXPERIMENT RESULT RELATING TRACK HEIGHT TO SCANNING SPEED GIVEN A LASER POWER OF 850W AND A POWER FLOW RATE OF 12gpm.

between node A and D is longer. The zigzag path generation method is summarized below:

Input *(2D Shape S, Zigzag Path Interval t)*
Output: *Zigzag path*
Begin
GetBoundingBox (S) $\rightarrow$ *BB*
GetPathOrientation (BB) $\rightarrow \overrightarrow{DP}$
GetTopLocation(BB) $\rightarrow$ *TP*
GetIntersectionPoint $\rightarrow$ *IP*
GetIntersection(TP, S)
While *(no more intersection)*
If *(First Intersection)*
CreateNode $\rightarrow$ *NodeList*
Else
If *(Topological relationship changes)*
EndCurrentNode
PutCurrentNodeIntoGraph $\rightarrow$ *NG*
CreateNode $\rightarrow$ *NodeList*
Else
PutPathIntoNode
End
End
ComputeNextIntersectionPoint (t, $\overrightarrow{DP}$*)*
EndWhile
Do breath Search in NG
OutputZigZagPath
End

4.2 Offset tool-path generation

The offset tool-path for machining processes has been researched widely. Simple offset or contour tool-path has been common practice in industry for a while. Although such path pattern has been used to generate tool-path for metal deposition process, the character of material additive process is still not fully incorporated into tool-path generation. For

Copyright © 2010 by ASME

Downloaded From: https://proceedings.asmedigitalcollection.asme.org on 06/27/2019 Terms of Use: http://www.asme.org/about-asme/terms-of-use

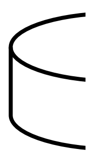
example, the different overlap of tool path does not change the final machined shape for a regular machining process.

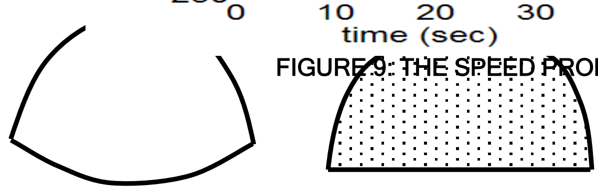
However, the different overlaps in the tool-path for a laser metal deposition process have huge impact on layer height. The research on offset tool-path generation in this paper is to maintain the deposition height by varying the speed.

4.2.1 Characters of the metal deposition process

Deposition height vs. laser scanning speed

The deposition height is determined by the scanning speed with constant laser power and material (or powder) feed rate. Figure 7 shows the relationship between the deposition height and scanning speed. The height is the average of 5-layer single track deposition. The experiment is performed using LAMP system at Missouri S&T. The tracks are measured using a 3D laser scanner (NEXTENGINE Desktop 3D scanner, Model 2020i). Therefore, changing the scanning speed is able to vary the deposition height.





(b) Bell shape for a deposition bead

FIGURE 8: THE IDEAL AND REALISTIC DEPOSITION BEAD SHAPE

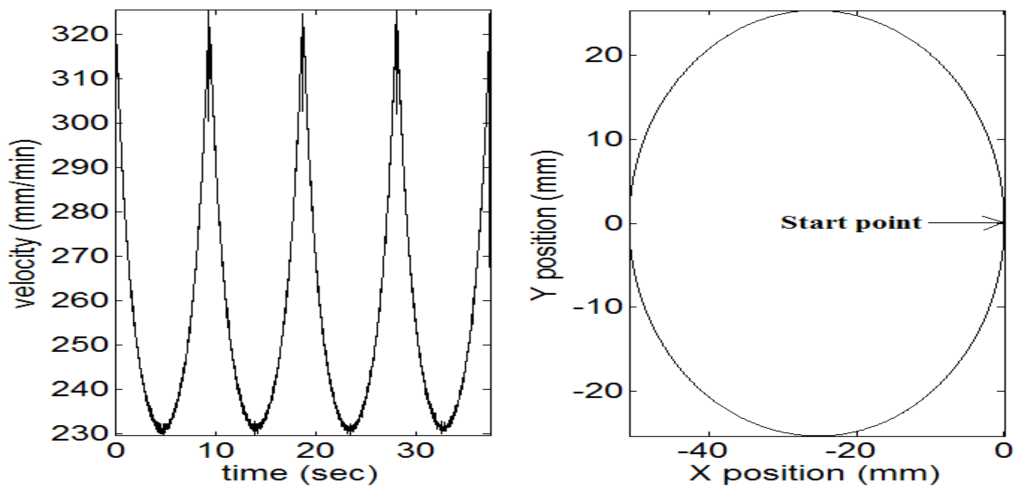


FIGURE 9: THE SPEED PROFILE OF FADAL 3016L FOR A CIRCLE

Deposition bead shape

The ideal shape of a deposition bead is a cap as shown in Figure 8(a). However, due to the heat transfer phenomena, the center of the laser spot always has the highest temperature. For most of the materials, the deposition bead is a bell-like shape as shown in Figure 8(b). The height profile can be modeled as,

$$H_r = f(r) \;\; r \leq R \tag{1}$$

where R is the radius of laser spot.

An empirical model can be constructed for different materials with different laser scanning speed.

Overlap effect

The overlap of the tool-path in the machining process is to guarantee that the machining tool covers the entire area to be machined. In laser metal deposition process, the overlap also serves another purpose. The cross section of a deposition track for most metal materials is also bell-like; thus the overlap between tracks also helps to maintain the height. It is obvious that a small overlap leads to less deposition and a large overlap can lead to over deposition. The deposition P of any location can be given by

$$H_p = \sum_{i=1}^{n} \alpha_i f(r_i) \tag{2}$$

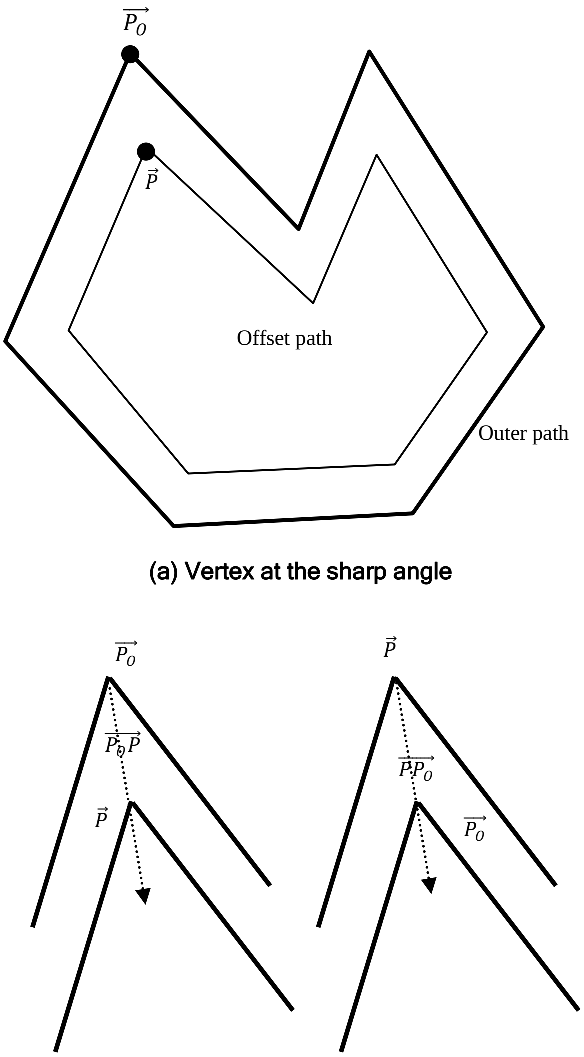
where α_i is an empirical coefficient for different metal materials. There are n deposition locations nearby location P with a distance less than the laser spot or bead size. This model considers the add-on effect of the material additive process.

4.2.2 Realistic Speed profile

In typical process planning, a nominal speed is used for entire deposition path. However, due to dynamics of each axis, each axis has to accelerate or decelerate while changing the travel direction; thus, the machine cannot maintain an ideal constant speed. For Fadal CNC machine used in LAMP system, it is observed that the speed is dropped dramatically (more than 90%) when make a sharp angle turn (angle less than 20°). Figure 9 shows a speed profile for a circle. The speed variation is about 35%. The speed variation is lowered to 5% when a polygon approximated circle is used. Based on

Copyright © 2010 by ASME

Downloaded From: https://proceedings.asmedigitalcollection.asme.org on 06/27/2019 Terms of Use: http://www.asme.org/about-asme/terms-of-use



(a) Vertex at the sharp angle

(b) Convex vertex moving direction

(c) Concave vertex moving direction

FIGURE 10: TOOLPATH DIRECTION ADJUSTMENT ILLUSTRATION

these observations, the strategy of offset path adjustment is to use polygon segments to remove the sharp angle.

4.2.3 Tool-path adjustment approach

Sharp angle identification and processing

Assuming a B-Spline or a polygon model in the the input geometry, the sharp angle point can be identified by tracing the angle between the edges. In this offset adjustment process, the tool-path along the boundary is not changed in order to maintain the required shape; thus the adjustment takes place on the path next to the boundary. Let $\vec{P}$ be the point at a sharp angle on the offset path and $\overrightarrow{P_O}$ is the corresponding point on the outer path, shown in Figure 10. In order to adjust the tool-

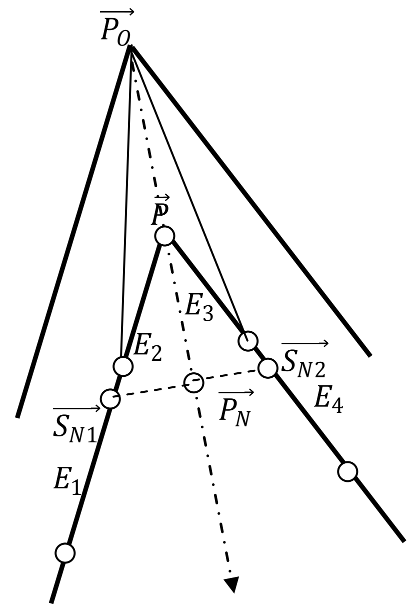


FIGURE 11: THE NEW POINT IDENTIFICATION

path and remove the sharp angle, it is obvious that the point $\vec{P}$ should move along the

direction $\overrightarrow{P_O P}$ shown in Figure 10(b). However, the moving direction is $\overrightarrow{P P_O}$ for the concave vertex.

$\overrightarrow{P_O P}$ or $\overrightarrow{P P_O}$ is along with bisector line. Moving $\vec{P}$ along this direction can have the equal impact on the neighboring path since the points on the bisector line have equal distance to both edges which form the angle. The first guessing point is given by

$$\overrightarrow{P_N} = \vec{P} + \vec{L} * a * T \qquad (3)$$

where T is the track width, α is a coefficient for track width and $0.25 < a < 0.5$. a is determined by the sharpness of the angle. The sharper the angle, the greater α is.

When a new point $\overrightarrow{P_N}$ is created, the edges which are around the vertex $\vec{P}$ are checked. The following procedures for convex vertex are applied:

1. Find the vertices of the edge.
2. Identify points along the edges of the angle so that the length of vectors which they form with $\overrightarrow{P_O}$ are just longer than $\overrightarrow{P_O P}$. In Figure 11, $\overrightarrow{S_{N1}}$, $\overrightarrow{S_{N2}}$ are created points.
3. Form the new edges $\overrightarrow{S_{N1} P}$, $\overrightarrow{S_{N2} P}$ and put them into edges list and remove the un-needed edges, edge E_2 , E_3 are removed.

Void fill path

Copyright © 2010 by ASME

Downloaded From: https://proceedings.asmedigitalcollection.asme.org on 06/27/2019 Terms of Use: http://www.asme.org/about-asme/terms-of-use

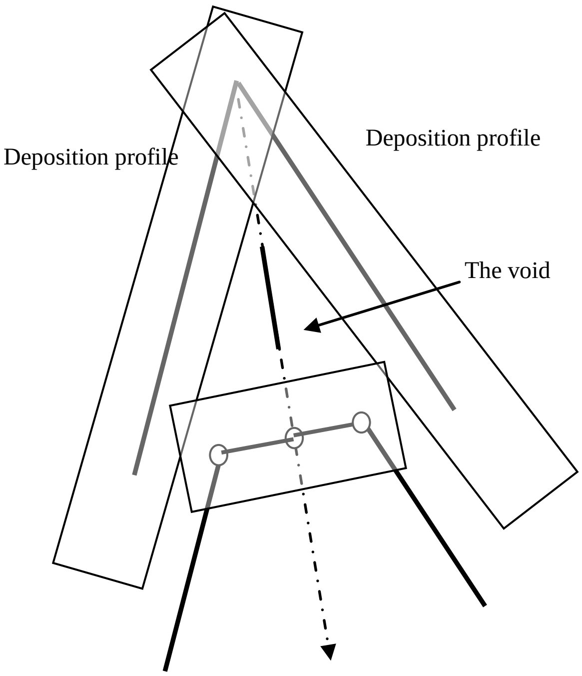


FIGURE 12: THE VOID CREATED AFTER TOOL-PATH ADJUSTMENT

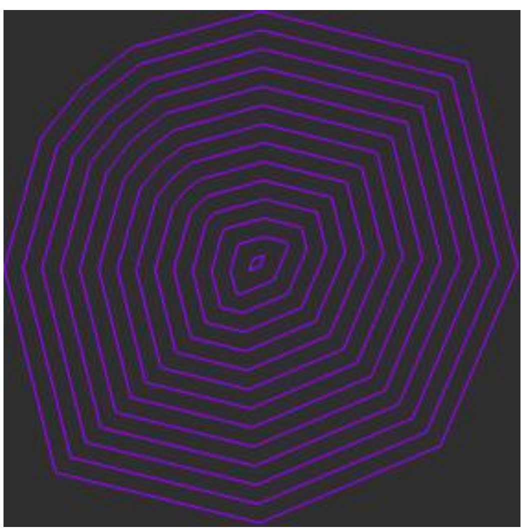
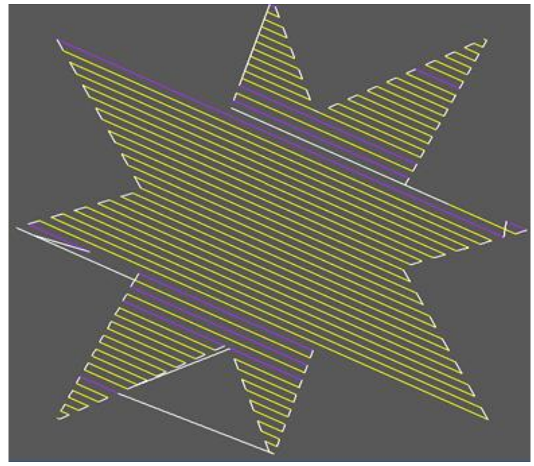


FIGURE 14: AN OFFSET EXAMPLE WITHOUT PATH ADJUSTMENT

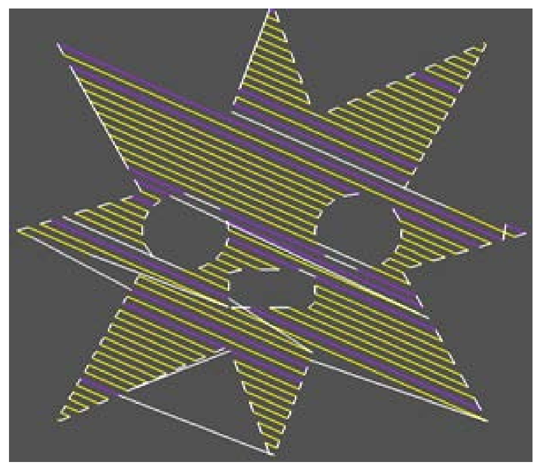
The other issue is that some void appears when the tool-path adjustment is performed. As shown in Figure 12, the void occurs in the center area. An extra path is created to fill the gap which is given by:

$$\vec{S} = \vec{P} + \vec{L} * \left(\frac{b}{\sin(\alpha/2)} + 1\right) * T \quad (4)$$

$$\vec{E} = \overrightarrow{P_N} - \vec{L} * T \quad (5)$$



(a) An example of a star



(b) An example of a star with hole

FIGURE 13: ZIGZAG PATH EXAMPLES

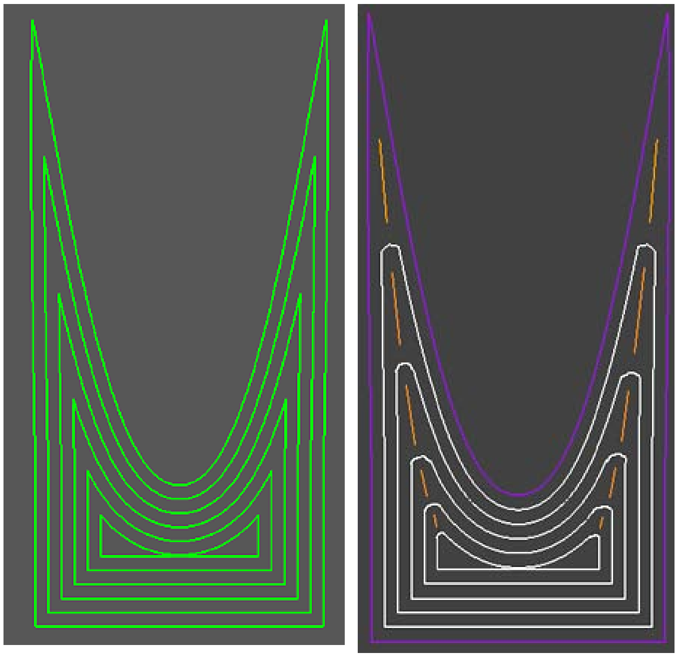
where $\vec{S}$ and $\vec{E}$ are the vertices of the edge, α is the angle at the corresponding point at the outer path. b is a coefficient for overlap effect.

5. EXAMPLES

The presented algorithm has been implemented in VC++ using OpenCascade geometry kernel. Figure 13 (a) shows a zigzag path example. The total deposition length is 327.0 mm and the length of idle path is 40.8mm so the efficiency is 88.9%. A random orientation is selected to generate the path and the efficiency is dropped to less than 80%. Figure 13 (b) shows the similar example with hole. However, the efficiency is dropped to 80% as the idle path has to jump over holes. The proposed work can generate efficient tool-path for most cases. However, authors also found that this approach does not obtain the most efficient path for very few cases. The reasons for this issue can be:

Copyright © 2010 by ASME

Downloaded From: https://proceedings.asmedigitalcollection.asme.org on 06/27/2019 Terms of Use: http://www.asme.org/about-asme/terms-of-use



(a) Before adjustment (b) After adjustment

FIGURE 15: AN OFFSET EXAMPLE WITH PATH ADJUSTMENT

- The bounding box with the greatest ratio is not found due to search accuracy
- The breath searching for the hierarchy structure does not yield the best solution.

In the research presented in this paper, the sharp angle is defined as less than 90°. In Figure 14, an offset path without adjustment is shown. No sharp angle in this shape is found thus no adjustment is made. Figure 15 shows an offset example with and without adjustment. It is clearly shown that all sharp angles (greater than 90°) are removed. On the other hand, the offset path adjustment is only based on angle analysis and does not consider the overlap effect in the close path situation as shown in Figure 15.

6. CONCLUSION

In this paper, approaches to generate the zigzag path and offset path are presented. The bounding box with the greatest ratio and hierarchy graph structure is very helpful in finding an efficient way to connect zigzag path. For most cases, the approach is suitable to find an efficient solution. An offset tool-path adjustment based on overlap and speed profile is studied. The sharp angles in the geometry causing inconsistency in the speed can be removed and a void fill method based on overlap and bead profile is studied.

In the future, the matrix-based offset path can be studied to fully utilize the deposition profile. However, such an approach is very time consuming. Therefore, a quick offset path generation for layers will be needed. Mapping an offset path to different layer could provide a solution.

ACKNOWLEDGEMENTS

This research was supported by the National Science Foundation grants DMI-9871185 and IIP-0637796, and a grant from the U.S. Air Force Research Laboratory contract # FA8650-04-C-5704. Support from Boeing Phantom Works, Product Innovation and Engineering, LLC, Spartan Light Metal Products Inc, MISSOURI S&T Intelligent Systems Center, and the MISSOURI S&T Manufacturing Engineering Program, is also greatly appreciated.

REFERENCE:

1. Erzincanli F., Ermurat M., "Comparison of the Direct Metal Laser Fabrication Technologies", 2nd International Conference on Responsive Manufacturing, University of Gaziantep, 2002.
2. Mazumder, J.; Schifferer, A.; and Choi, J. (1999). "Direct materials deposition: designed macro and microstructure." Materials Research Innovations (v3, n3, 1999), pp 118-131.
3. Kao, J., and Prinz, F.B., "Optimal Motion Planning for Deposition in Layered Manufacturing", Proceedings of DETC'98, September 13 - 16, 1998, Atlanta, GA.
4. Park, S.C. and Choi, B.K., "Tool-path planning for direction-parallel area milling", Computer-Aided Design 32 (2000) 17–25
5. Tiller, W., and Hansen, E.G., "Offset of Two-Dimensional Profiles", IEEE Computer Graphics and Applications, 1984:36-46.
6. Remfield, R.F., "IGB-Offset for Plane Curves-loop Removal by Scanning of Interval Sequences", Computer Aided Geometric Design 1998:339-375.
7. Park, S.C., and Choi, B.K., "Uncut Free Pocketing Tool-Paths Generation Using Pair-Wise Offset Algorithm", Computer –Aided Design. 2001:33:739-746.
8. Choi, B.K., and Park, S.C., "A Pair-Wise Offset Algorithm for 2D Point-Sequence Curve", Computer – Aided Design. 1999:31(12):735-745.
9. Kokichi, S., "Degeneracy and Instability in Geometric Computation", Proceedings of IFIP WG5.2 GEO-6 Conference in Tokyu University, December 7-9, 1998, pp.5-15.
10. Kunnayut Eiamsa-ard, F.W. Liou and Robert G. Landers, "Toward Automatic Process Planning of a Multi-axis Hybrid Laser Aided Manufacturing System: Skeleton-based Offset Edge Generation", ASME. 2003.
11. Liou, F.W.; Landers, R.G.; Choi, J.; Agarwal, S.; Janardhan, V.; Balakrishnan, S.N.,(2001) "Research and Development of a Hybrid Rapid Manufacturing Process,"

 Copyright © 2010 by ASME

Downloaded From: https://proceedings.asmedigitalcollection.asme.org on 06/27/2019 Terms of Use: http://www.asme.org/about-asme/terms-of-use

Proceedings of the Twelfth Annual Solid Freeform Fabrication Symposium, Austin, TX, pp. 138, August 6-8, 2001.

12. Zhou, Chi; Chen, Yong and Waltz, Richard, "Optimized Mask Image Projection for Solid Freeform Fabrication", Proceedings of the ASME 2009 International Design Engineering Technical Conferences and Computers and Information in Engineering ConferenceAugust 30-September 2, 2009, DETC2009/DAC-86268 San Diego, California, USA
13. Wang, Hongcheng; Peter, Jang and Stori, James A.," A Metric-Based Approach to Two-Dimensional (2D) Tool-Path Optimization for High-Speed Machining", Journal of manufacturing science and engineering, 2005, vol. 127, No.1, pp. 33-48
14. Liou, F.W.; Landers, R.G.; Choi, J.; Agarwal, S.; Janardhan, V.; Balakrishnan, S.N.,(2001) "Research and Development of a Hybrid Rapid Manufacturing Process," Proceedings of the Twelfth Annual Solid Freeform Fabrication Symposium, Austin, TX, pp. 138, August 6-8, 2001.
15. Ruan, Jianzhong; Ren, Lan; Sparks, Todd E. and Liou, Frank "2-D Deposition Pattern And Strategy Study On Rapid Manufacturing," Proceedings of the 2006 ASME International Design Engineering Technical Conferences & Computers and Information In Engineering Conference, Philadelphia, PA from September 11-13, 2006.

 Copyright © 2010 by ASME

Downloaded From: https://proceedings.asmedigitalcollection.asme.org on 06/27/2019 Terms of Use: http://www.asme.org/about-asme/terms-of-use