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Motion Planning for a Direct Metal Deposition Rapid Prototyping System

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Abstract

A motion planning strategy was developed and implemented to generate motion control instructions from solid model data for controlling a robotically driven solid freeform fabrication process. The planning strategy was tested using a PUMA type robot arm integrated into a LENS™(Laser Engineered Net Shape) system. Previous systems relied on a series of x, y, and z stages, to provide a minimal coordinated motion control capability. This limited the complexity of geometries that could be constructed. With the coordinated motion provided by a robotic arm, the system can produce three dimensional parts by "writing" material onto any face of existing material. The motion planning strategy relied on solid model geometry evaluation and exploited robotic positioning flexibility to allow the construction of geometrically complex parts. The integration of the robotic manipulator into the LENS™ system was tested by producing metal parts directly from CAD models.

1 Introduction

The subject of this paper is a motion planning strategy implemented to increase the ability of the LENS™ (Laser Engineered Net Shape) process to produce geometrically complex parts. The planning strategy was tested using a PUMA type robot arm integrated into a LENS™ system and was demonstrated by producing metal parts directly from CAD models.

The LENS™ [1,2] process produces structures by using a laser beam to form a molten pool of material on a substrate. Powder, blown into this molten pool, melts, and then fuses to form new material. Advancing the laser, pool, and powder around previously deposited material adds a new layer of material. Any previously deposited material can serve as the substrate for subsequent layers. Figure 1 illustrates the active components of the LENS™ process.

The process can produce parts using a variety of materials including: stainless steel alloys, titanium alloys, and tool steel alloys. The deposited material exhibits excellent material properties appropriate to the parent material. In addition the deposited materials have relatively small metallic grain sizes, a property which enhances wear resistance.

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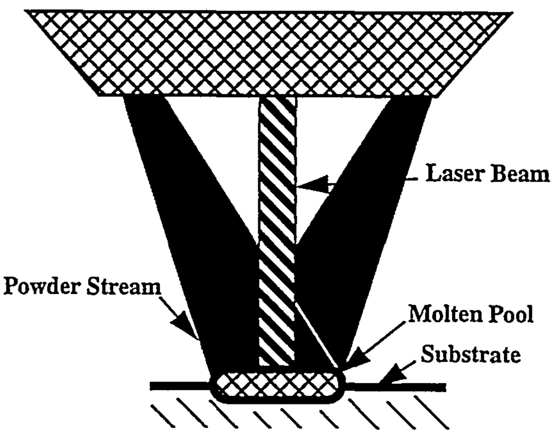

Figure 1: Schematic of the LENS™ process.

The LENS™ process is run by feeding a set of instructions to a motion controller. The instructions tell the controller how to move the laser relative to the part and when to turn the laser on and off. The capabilities of both the controller and the motion generating hardware directly influence the shapes of parts which can be successfully built.

2 Motion Control

With a few exceptions [3,4] the motion control systems used for LENS™ manufacturing are based on a personal computer combined with a motion control card and a series of linear and rotary motion stages. These motion control systems provide coordinated motion in three directions but are limited in their ability to provide any coordinated orientation control.

Initial efforts at increasing the geometric complexity of parts manufacturable using LENS™ focused on enhancing a 3 degree of freedom system with the addition of tilt and rotary stages. Using such a system to provide coordinated motion requires external calculation of joint positions based on a kinematic model of the system. The system is then instructed to move through a 'camming table' storing these positions. To achieve smooth motion the calculated joint values must be closely spaced in time. This complex approach was abandoned in favor of a commercially available robot and controller.

The move to an industrial robot and controller for coordinated motion control immediately provided access to forward and inverse kinematics calculations, speed control, and continuous interpolated motion. The kinematics available in the industrial controller allowed specification of

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movement along 6 degree of freedom paths in terms of locations and orientations in a working coordinate frame. Speed control for motion using the robot was achieved by specifying the time allowed for movement between equally spaced points along a path.

3 Geometry Constraints on LENS™

The offset angle, illustrated in Figure 3 is the geometry constraint that most limits the geometric complexity of parts that are manufacturable using LENS™. This angle is the amount by which succeeding layers of deposited material may overhang the previously deposited layers. This angle is strongly dependent on process parameters such as: laser power, traversal speed, material type, and beam quality.

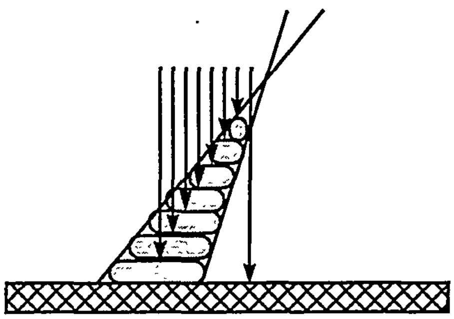

Figure 2: Consequence of exceeding offset angle in build up of layers.

The offset angle limitation is caused by the lower efficiency of deposition when the laser is near the edge of a part. This is illustrated in Figure 2 in which the vertical arrows signify the laser approach. Because the molten pool is typically larger than the size of the laser focus point the material deposition region during a pass is wider than the laser beam. If the next layer is shifted closer to the edge of the part, it can only do so by an acceptable fraction of the width of the previously deposited layer. A series of shifts larger than this amount will result in the eventual 'fall off' or 'loss of support' of the deposited material. When 'fall off' occurs the laser will no longer focus on the previous layer and useful deposition ends. The constraint of the offset angle ensures that parts manufactured using x, y, and z motion will have shapes which are extrusions in the direction of the laser approach direction.

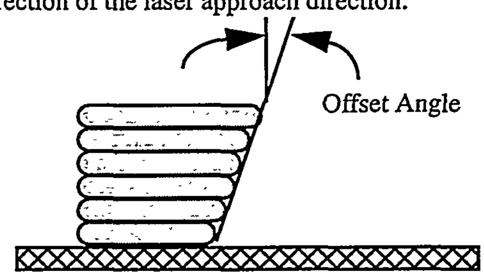

Figure 3: Offset angle formed by sequential layers.

The limitation imposed by the offset angle is avoided by changing the orientation between the deposition head and the part to ensure support for the next level of deposition. This is illustrated in Figure 4 where the approach direction of the laser is maintained tangent to the curve along which material is being deposited.

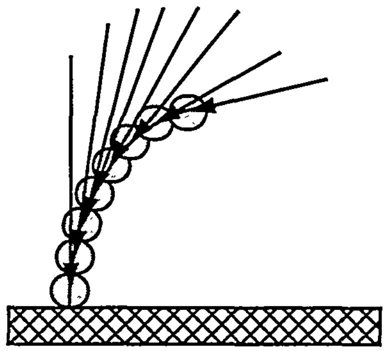

Figure 4: A shape exceeding the offset angle successfully deposited by varying the laser approach direction to ensure buildability.

Appropriate orientation is achieved by either moving the part or the deposition system. If the part is moved and the laser remains aligned with the vertical, then there is the added advantage that gravity drives the molten pool towards the supporting substrate. Gravity assists surface tension in holding the molten pool on the substrate. Moving the part relative to the laser beam makes the growing workpiece part of the payload of the motion system and limits the size of parts that can be built. Moving the laser head complicates the routing of the laser beam and powder feed lines.

4 Robot Installation

The LENS™ process is carried out in an inert (Argon) atmosphere inside a glove box. For this installation a specially sized glove box was constructed to accommodate the 60cm reach of the robot. The robot installed in the glove box is shown below in Figure 5. The robot is configured to hold the workpiece. This simplifies the routing of the laser and powder streams and also to reduces the safety issues involved in mounting a high powered laser on the end of a robotic arm. The windows of the glove box are covered with material formulated to block the reflections of the NdYAG laser. When sealed, the glove box system is considered a Class I laser device. Light fences are installed inside the glove box to halt the robot and close the laser shutter if the gloves were used during operation.

The robot is installed offset from the deposition head to allow effective manipulation with either a flat plate substrate holder in an 'elbow down' configuration or with an angled substrate holder in an 'elbow up' configuration.

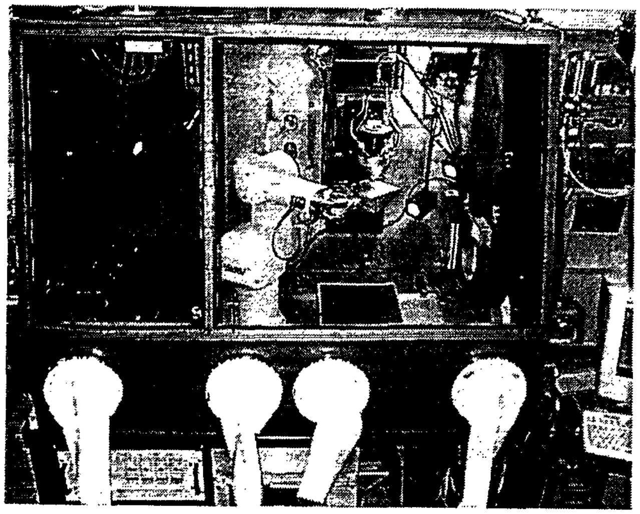

Figure 5: Robot installed in glove box.

5 Motion Planning Algorithm and Implementation

5.1 Previous Work

The bulk of the previous work dealing with motion planning for rapid prototyping and solid free-form fabrication [5] focuses on systems such as Stereolithography Apparatus (SLA), Fused Deposition Modeling (FDM), Laminated Object Manufacturing (LOM), Selective Laser Sintering (SLS), and Solid Ground Curing (SGC). In all of these processes, parts are composed of a series of planar layers which are sequentially deposited along the build up direction [6]. In [7] algorithms are supplied to determine if a part can be manufactured without support. In [8] and [9] the optimal construction of such supports is considered. The authors of [10,11] and [12] offer procedures for improving the accuracy and finish of parts. The issues of minimizing stair-step error, minimizing the volume of supports, and minimizing the contact area of supports are addressed in combination in [13] and [14].

The SLA type processes addressed above define parts as x, y, and z locations in a slice plane. The work presented here focuses on exploiting the ability of a robotically manipulated system to control orientation as well as location. Adding orientation as part of the process definition makes it possible to avoid the limitation of the offset angle.

5.2 Strategy and Implementation

The motion planning algorithm implemented for robotic control slices the target geometries with a plane swept along the build up direction and formulates the resulting contours into motion control instructions appropriate for constructing the specified geometry. With some exceptions [15] most motion planning implementation work with faceted data. This implementation works directly from the exact part representation supplied by an ACIS [16] solid model. Working directly from the solid model representation eliminates some of the artifacts that faceted geometry introduces to a part representation.

This implementation focuses on increasing the geometric complexity of manufacturable parts and not on increasing the topological complexity. Figure 6 shows a part with simple geometry (planar faces) but complex topology and a part with complex geometry (multiple NURBS surfaces) and simple topology. This implementation assumes that a user will manually decompose a topologically complex part into a set of topologically simple but geometrically complex parts which can each be constructed sequentially. An effort to automate this decomposition process is presented in [17].

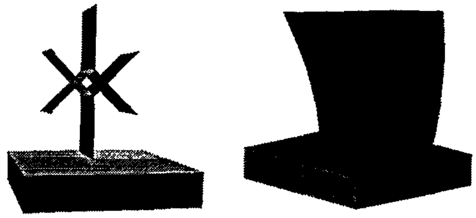

Figure 6: A: Simple geometry and complex topology, B: Simple topology and complex geometry.

The deposition process for solid parts is an alternating series of perimeter depositions and internal volume rasterizations. The perimeter deposition builds up what will be the external surface of the part and provides a border for the rasterization step which fills in the solid. The perimeter construction and rasterization steps are shown below in Figure 7.

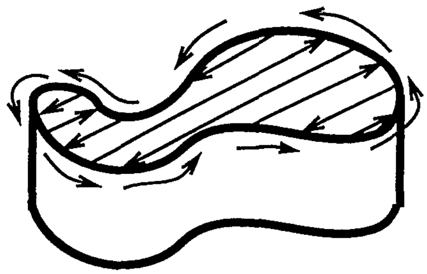

Figure 7: Perimeter and rastering steps of part construction.

In this implementation the limitation of the offset angle is overcome by building the perimeter of each level such that during the perimeter deposition the direction of laser approach is tangent to the surfaces and edges of the part under construction. As an example, the approach directions for the construction of the perimeter of a slice through a sphere are a set of vectors tangent to the sphere's surface. While depositing the perimeter defined by the slice through the sphere, the focus of the laser moves between points on the perimeter of the slice such that at each point it is aligned tangent to the sphere's surface. For the SLA type construction processes, specification of a layer is in terms of a set of locations in x, y, and z. In this process a layer is defined as a set of locations and orientations. For contoured surfaces this ensures that the laser beam will impinge directly on previously deposited material.

The motions for perimeter construction are calculated by first intersecting a plane with the solid model. The resulting geometry consists of one or more loops of one or more edges that bound a region of the solid. These loops are traversed to find a sequence of points describing the perimeter. The appropriate laser approach direction at each of these points is calculated by taking the cross product of the part's surface normal and the direction of loop traversal. This direction is then adjusted by a rotation around the surface normal to ensure that the approach direction is tangent to the edges of the underlying surfaces of the part. This ensures that the approach direction varies slowly around the perimeter of a part despite the rapid changes in surface normal that occur across surface edges.

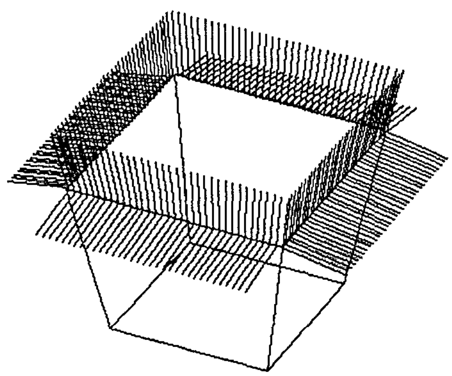

Figure 8: A drafted shape showing the surface normals and adjusted laser approach directions.

The rastering data for filling in a solid part (for a hollow part rastering is omitted) is calculated by firing parallel rays, in the slice plane, at the solid model and moving between the points of intersection (Figure 9). Since the perimeter around the rastering pattern has already been constructed, support for the material deposited during rasterization is guaranteed, and the laser approach direction for the rastering process is the opposite of the build up direction.

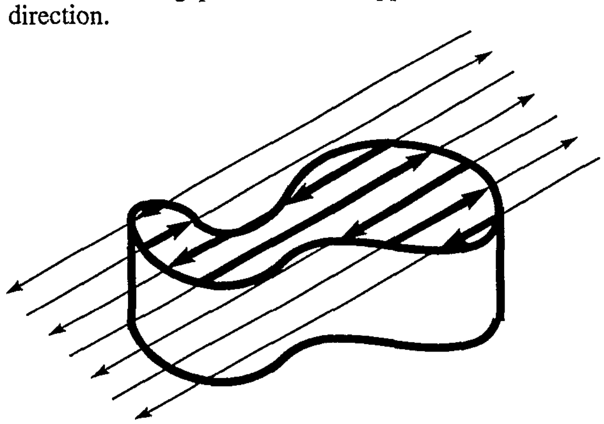

Figure 9: Body tested with rays to define rastering pattern.

The positions and orientation are originally calculated in the solid model's coordinate frame. They are subsequently transformed into locations and orientations in the robot's working frame that produce the correct relative motions between the part and the deposition head. This transformation consists of the two steps illustrated in Figure 10. The solid outline is a cup shaped part that is being built. The grey arrows indicate the x and z axes of the robot's working frame. The descending arrow represents the laser. The cross-hairs mark the position being transformed. The dashed arrow shows the approach direction and how it is transformed. First, the approach direction is rotate by 180 degrees about the laser. Next, the position is rotated through half of the angle between the original approach direction and the rotated approach direction. Finally, the coordinates of the position are negated.

Correspondence between the working coordinate frame of the robot and the part coordinate frame in which motion planning is performed is ensured by specifying the origin of the working coordinate system at the focal point of the laser and aligning the axes of the working coordinate frame with the surface of the substrate and the laser.

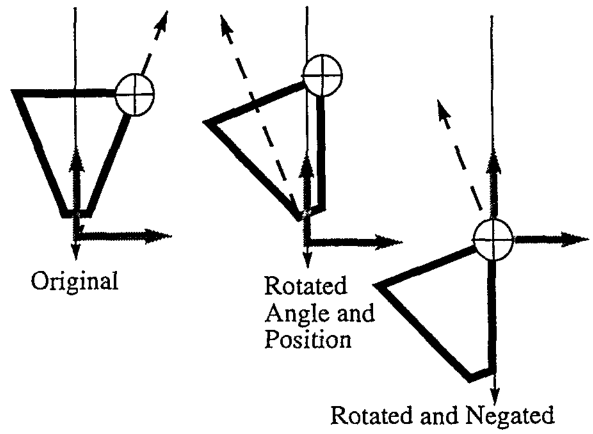

Figure 10: Transformations applied to position and orientation data.

6 Communication

The motion control data for even a small part may consist of several Mb of data. Since the program space of the motion controllers is limited, the motion control data is loaded into program memory incrementally. Unfortunately the controller used for this system does not allow movement during while data was being loaded. For this implementation a program running on the controller reads a series of locations from a data file and directs the robot arm to move smoothly through these positions. After moving through these positions, the robot returns to a safe location and loads the next set of location and orientation data. A protocol that allowed the loading of the next set of data while the current set of data is in use would substantially improve material processing speed.

7 Demonstration Geometries

The part illustrated in Figure 11 is a rendering of one of the geometrically complex parts constructed using the robotic LENS™ system and motion planning software. The part is specified by a single face defined by a rectangle 60 cm by 20 cm that is twisted 90 degrees about one of its long edges. The surface geometry is represented by a NURBS surface with coordinates isoparametrically mapped between the edges.

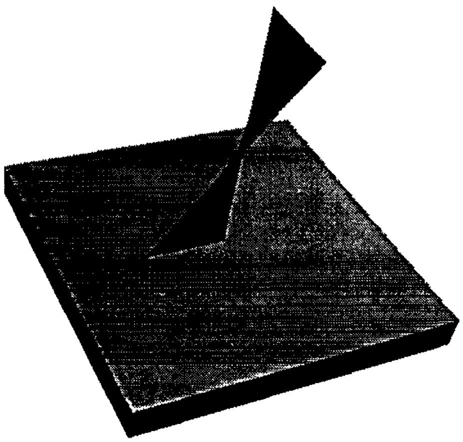

Figure 11: Rendering of CAD model of a demonstration part.

The part shown in Figure 11 is shown constructed from 316 stainless steel in Figure 12. The manufacturing process consisted of the following steps: construction of a model of the part, specification of a build-up direction, generation of motion control information, execution of motion control program to manufacture the part. The motion planning step for this part consumed two minutes on an SGI Octane workstation. The deposition process required 45 minutes on the LENS™ system.

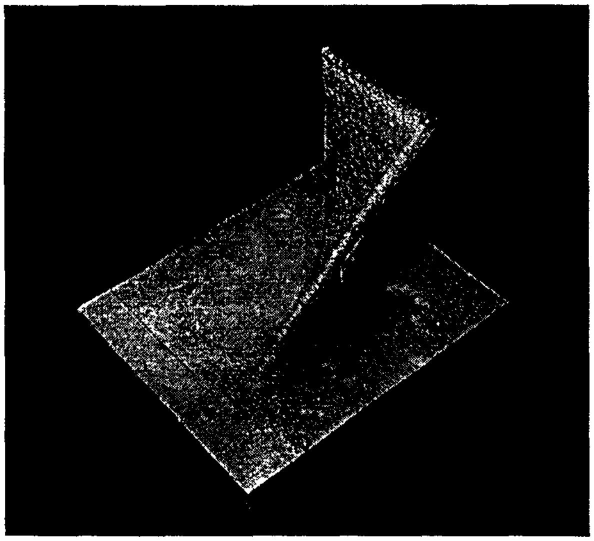

Figure 12: Photograph of a part with 316 stainless steel directly from a CAD model.

8 Summary and Conclusions

The robotic arm integrated into the LENS™ system significantly expanded the types of parts that could be constructed.

The motion planning algorithm successfully processes solid models into motion control instructions that could produce a part.

Using a commercially available robotic arm and controller to provide coordinated motion control is a simpler and quicker solution than implementing a similar capability using a custom controller and sequential stages.

None of the controllers considered for this application provide sufficient data transfer mechanisms to allow uninterrupted processing. The controllers have insufficient memory to hold the entire motion plan in memory, and to not have an avenue for allowing continuous coordinated movement while data transfer is occurring.

References

[1] M. Griffith et al., "Laser Engineered Net Shaping (LENS™) for the Fabrication of Metallic Components", *The 1996 ASME International Mechanical Engineering Congress and Exposition,* Atlanta, GA, USA, 11/17-22/96

[2] D. Keicher, L. Romero, C. Atwood, M. Griffith, "Laser Metal Deposition of Alloy 625 for Freeform Fabrication", *Proceeding of the P/M Symposium on Laser Manufacturing*, 1996 World Congress on Powder Metallurgy and Particulate Materials, Washington D. C. June 1996.

[3] "Laser Direct Line Setup" in: Mechanical Engineering, May 1999, p 18.

[4] J. Mazumder, J. Choi, K. Nagaratham, Koch, J. Choi, "The Direct Metal Depositon of H13 Tool Steel for 3-D Components", *Journal of Metals*, May 1997, pp. 55-60.

[5] J. Conley, H. Marcus, "Rapid Prototyping and Solid free-form Fabrication", *Journal of Manufacturing Science and Engineering*, Vol 119, pp 811-816, 1997.

[6] P. Jacobs, Rapid *Prototyping & Manufacturing : Fundamentals of StereoLithography*, McGraw-Hill, 1992.

[7] B. Asberg, G. Blanco, P. Bose, J., Garcis-Lopez, M. Overmars, G. Toussaing, G. Wilfong, B. Zhu, "Feasability of Design in Stereolithography", *Algorithmica* 19 (1997) 61-83

[8] S. Allen, D. Dutta, "Determination and Evaluation of Support Structures in Layered Manufacturing", *J. Design Manufacturing* 5 (1995) 153-162

[9] D. Frank, G. Fadel, "Preferred Direction of Build for Rapid Prototyping Processes, *Proceedings of the 5th International Conference on Rapid Prototyping*, 1994pp. 191-200.

[10] M. Bablani, A. Bagchi, "Quantification of Errors in Rapid Prototyping Processes and Determination of Preferred Orientation of Parts", *Transactions of the 23rd North American Manufacturing Research Conference* 1995.

[11] P. Lan, S. Chou, L Chen, D. Gemmill, "Determining Fabrication Orientations for Rapid Prototyping with Stereolithography Apparatus", *Computer-Aided Design*, Vol. 29, No. 1, pp. 53-62, 1997.

[12] A. Dolnec, I. Makela, "Slicing Procedures for Layered Manufacturing Techniques", *Comput. Aided Design* 26 (1994) 119-126.

[13] J. Majhi, R. Janardan, M. Smid, P. Gupta, "On Some Geometric Optimization Problems in Layered Manufacturing", *Computational Geometry* 12 (1999) 219-239.

[14] J Majhi, R. Janardan, J. Schwerdt, M. Smid, P. Gupta, "Minimizing Support Structures and Trapped Area in Two-Dimensional Layered Manufacturing",*Computational Geometry*, No. 12, 1999, pp241-267.

[15] P. Vuyyuru, C. Kirschman, G. Fadel, A. Bagchi, C. Jara-Almonte, "A NURBS-Based Approach for Rapid Produce Realization", *Proceedins of the 5th International Conference on Rapid Prototyping*, June 12-15, 1994, Dayton, Ohio, pp 229-239.

[16] *ACIS 3D Toolkit 4.0 On-line Documentation*, Spatial Technology Inc., Boulder Co. 1998

[17] K. Ramaswami, Y. Yamaguchi, F. Prinz, "Spatial Partitioning of Solids for Solid Freeform Fabrication", *Proceedings of the 4th Symposium on Solid Modeling and Applications*. May 14-16, Atlanta, Ga. 1997, pp. 346-353.