Development of a Low-cost Parallel Kinematic Machine for Multi-directional Additive Manufacturing

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ABSTRACT

Most additive manufacturing (AM) processes are layer-based with three linear motions in the *X*, *Y* and *Z* axes. However, there are drawbacks associated with such limited motions, e.g. non-conformal material properties, stair-stepping effect, and limitations on building-around-inserts. Such drawbacks will limit additive manufacturing to be used in more general applications. To enable 6-axis motions between a tool and a work piece, we investigate a Stewart mechanism and developed a low-cost prototype system for multi-directional additive manufacturing processes such as the Fused Deposition Modeling (FDM) and CNC Accumulation. The technical challenges in developing such an AM system are discussed including the hardware design, motion planning and modeling, platform constraint checking, tool motion simulation, and platform calibration. Several test cases are performed to illustrate the capability of the developed multi-directional additive manufacturing system.

KEYWORDS:
Additive manufacturing, multi-direction, parallel kinematic machine, fused deposition modeling, building-around-inserts.

1 Introduction

Additive manufacturing (AM) processes can directly fabricate three-dimensional (3D) computer-aided design (CAD) models by controlling the selective accumulation of materials. Most AM processes are layer-based, that is, a given 3D model is first sliced into a set of two-dimensional (2D) layers; accordingly, a physical part is fabricated by stacking the sliced 2D layers together to approximate the given CAD model. An example of a tilted rod (*AB*) is shown in Figure 1. For such layer-based AM processes, only the linear motions in the *X*, *Y* and *Z* axes are required.

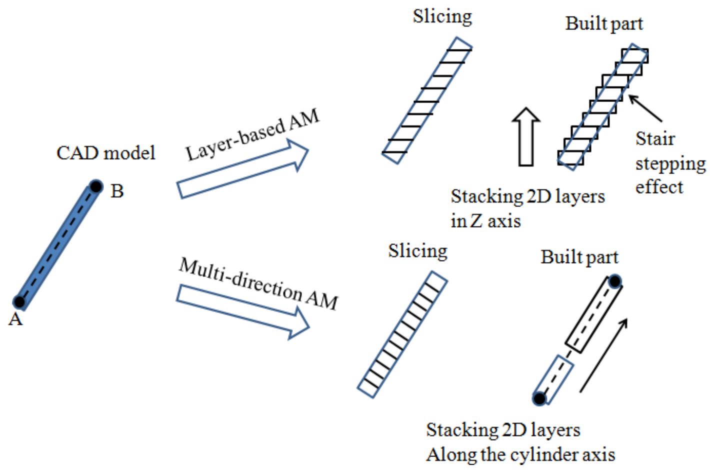


Figure 1: A schematic illustration of additive manufacturing process.

The layer-based fabrication approach has many benefits. For example, (1) tool path planning and hardware design are simplified; and (2) complex shapes that are impossible to be made before can be fabricated. However, there are also drawbacks associated with the layer-based fabrication approach. For example, (1) the surface finish is poor due to the stair stepping effect (refer to rod *AB* in Figure 1). (2) Also the material property of a geometric feature will depend on the building direction that is used in the fabrication process. Consequently, the material property of a tilted rod in different tilting angles will be different. In addition, (3) it would be difficult to build parts around inserts (e.g. an electric or optical component) due to the limited tool motions that are allowed in the system.

To address the problems of the layer-based AM processes, various methods have been proposed. For example, controlled cure depth [2, 3], post-processing [4, 5] and meniscus methods [6] have been developed for improving surface finish; and techniques such as model shape modification [7] and hybrid process development [8] have been employed to enhance the fabrication capability of building-around-inserts. However, most approaches can only improve one or a few drawbacks in a limited fashion mainly due to the use of a single build direction (*Z* axis) and a uniform layer thickness in the building process. In comparison, multi-directional AM processes, in which materials are added along multiple directions using non-uniform layer thickness (refer to Figure 2), can address the limitations of the layer-based AM processes. In the future AM process development, both layer-based and non-layer-based fabrication approaches may be required in the material deposition process.

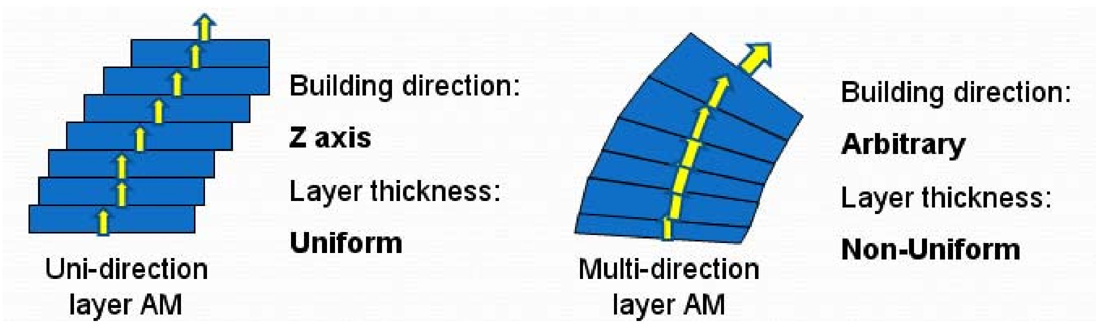


Figure 2: Comparison between the layer-based and multi-directional AM processes.

To achieve multi-axis motion between the accumulative tool and the workpiece, multi-directional AM processes can be classified into (1) **platform based** and (2) **accumulative tool based** approaches.

(1) Platform based approaches. Multi-directional fabrication can be achieved by rotating the platform in order to orientate the workpiece related to the accumulative tool. For example, a customized compliant parallel kinematic machine is presented in [9] for the Multi-Direction Layered Deposition (MDLD) process. The machine is comprised of two parts: a *X*-*Y* overhang head unit, and a workpiece orientation unit to rotate the built part to have a building direction that is aligned to the head unit. Consequently the deposition head can add materials from different orientations. The Laser Direct Casting (LDC) process [10] uses a similar approach by rotating built parts to achieve multi-directional fabrication. A multi-directional UV lithography process at micro- and nano- scales is also discussed in [11], in which two step motors are used to control the tilting and rotational angles of the substrate. In the design of a laser direct metal deposition system [12] for repairing deep and internal cracks in metallic components, the laser beam is kept stationary while the workpiece is moved and rotated.

(2) Accumulative tool based approaches. In multi-directional AM processes, the accumulative tools, instead of the platform, can be oriented with multiple degrees of freedom. A multi-directional Direct Metal Deposition (DMD) system using a high-power laser is presented in [13-16]. The laser beam is focused onto a workpiece and produces a melt pool. Medal powders are injected into the melt pool by feeding with inert gas stream. In the system, the laser head is controlled by a 5-axis motion mechanism that allows deposition of given shapes. As shown in [16], the slicing direction can be arbitrary, and a number of layers with non-uniform thicknesses can be generated. Accordingly, the tool path planning software can convert CAD models into nozzle motions for multi-axis deposition. The Directed Light Fabrication (DLF) process [17] is another kind of direct metal deposition process that fuses inert-gas-delivered metal powders into the focal zone of a high powered laser beam. By using the multi-axis numerical control sequence tool paths, materials can also be deposited in varying orientations. For the fabrication of polymer-based objects, a Computer Numerically Controlled Accumulation (CNCA) process was developed [18], in which a fiber optical cable connected with a high power UV-LED is controlled by a 5-axis motion system to enable the X, Y, and Z axes translations and the A and B axes rotations. Therefore, the accumulative tool can cure liquid resin in various directions.

Compared with the tool based approaches, the platform based processes have simpler structures, especially when the system only needs a few degrees of freedom (DOFs). However, rotating the platform is less flexible with limited degrees of freedom. To enable 6-axis motions between a tool and a work piece, a Stewart mechanism is investigated in this paper for developing a low-cost multi-directional additive manufacturing system. Compared with the traditional translation and rotation based approach, the Stewart mechanism enables the system to be less bulky. Two kinds of accumulative tools including a FDM heating extruder and a fiber-optics-based CNC accumulation tool are considered. The rest of this paper is organized as follows. Section 2 introduces the hardware design based on the Stewart mechanism. The cost of the prototype system is also discussed. In section 3, a kinematic modeling and simulation software system is presented. Section 4 describes a calibration method to achieve improved accuracy of the parallel kinematic machine. Section 5 presents the data processing pipeline of the multi-direction AM system based on the machine. Section 6 demonstrates the part fabrication of the prototype AM system using a FDM heating extruder. Finally conclusions are drawn in section 7.

2 Hardware Design

The hardware components of our parallel kinematic machine are introduced in this section. To enable the 6-DoF motion of a tool with respect to a fixed frame, six length-changeable struts are used to connect a moving platform on which an accumulative tool is mounted. For each strut, one of its ends is connected to the moving platform by a 3-DoF joint, and another end is connected to a fixed base frame by a 2-DoF joint (refer to Figure 3). This 6-axis parallel kinematic machine is also called *Gough-Stewart* mechanism. In industry, this mechanism has been used in precision positioning system (e.g. Hexapod 6-axis parallel positioning systems from *Physik Instrumente*). However, the commercial systems are expensive with relatively small travel ranges (<50mm).

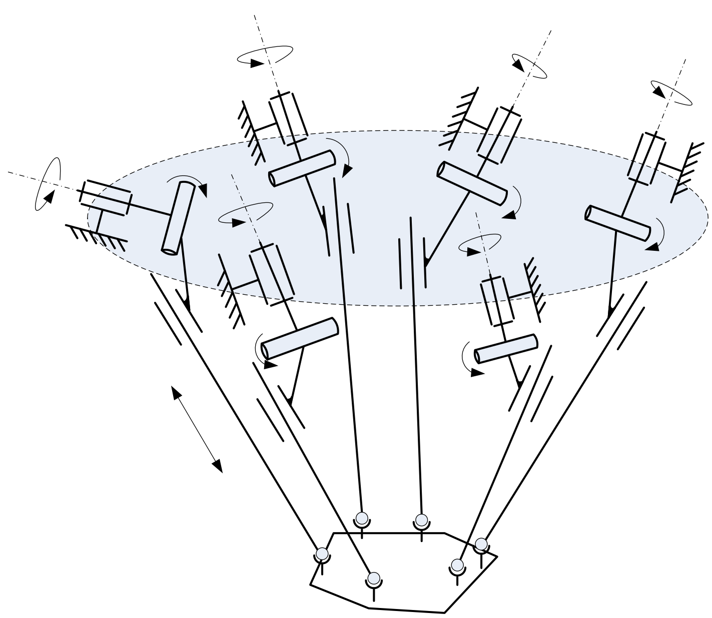


Figure 3: Schematic illustration of a Stewart mechanism.

Motivated by the recent progresses on developing low-cost 3D printers (e.g. *Makerbot*, *Solidoodle*, etc.), we investigated the development of a low-cost 6-axis parallel positioning system for additive manufacturing processes. As shown in Figure 3, the parallel kinematic machine is made up of six length-changeable struts. In our testbed, six ball screw linear actuators are used as the length-changeable struts. The linear actuators are connected in pairs to a hexagon moving platform by ball joints. Each motor body is mounted on a customized universal joint, which has 2-DoF motion relative to the fixed base frame.

The CAD model of the designed system is shown in Figure 4. In our testbed, we used linear actuators from Eastern Air Devices Inc. (Dover, NH). Its original lead-screw was replaced by a 1/4-16 ACME one with a length of 12". The system is controlled by a high performance 8-axis motion control board KFLOP+2KSTEP (Dynomotion Inc., Calabasas, CA). A motion parameter generation and control software system has been developed. The system can load in the G-code of tool paths, transform them into motion command parameters, and send them to the motion controller though 6 output pins in the KSTEP board. A photo of the built prototype system is shown in Figure 11. Based on the Stewart mechanism, relatively small motions of the linear actuators can lead to large motions of the tool on the moving platform. Hence the multi-directional AM system can have high fabrication speed.

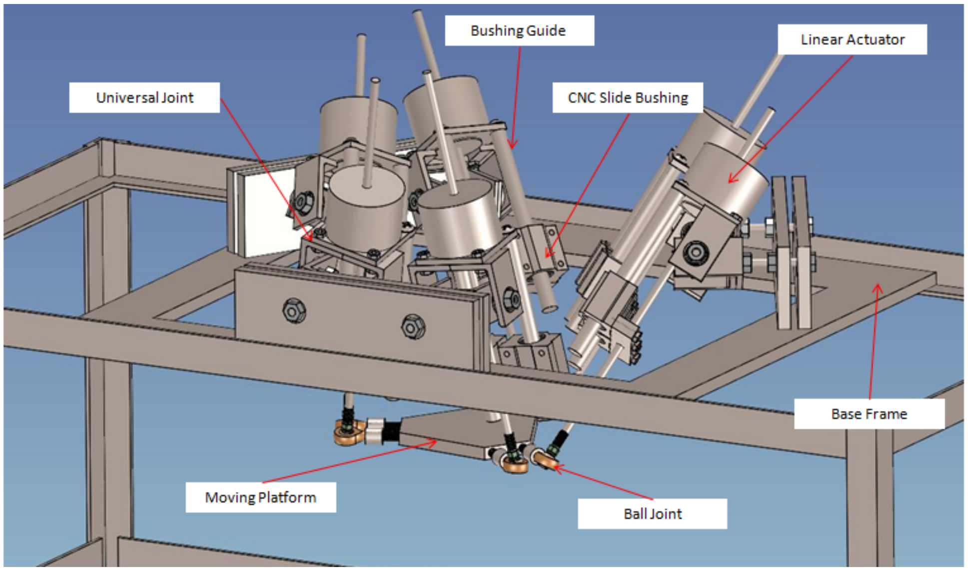


Figure 4: CAD model design of our parallel kinematic machine.

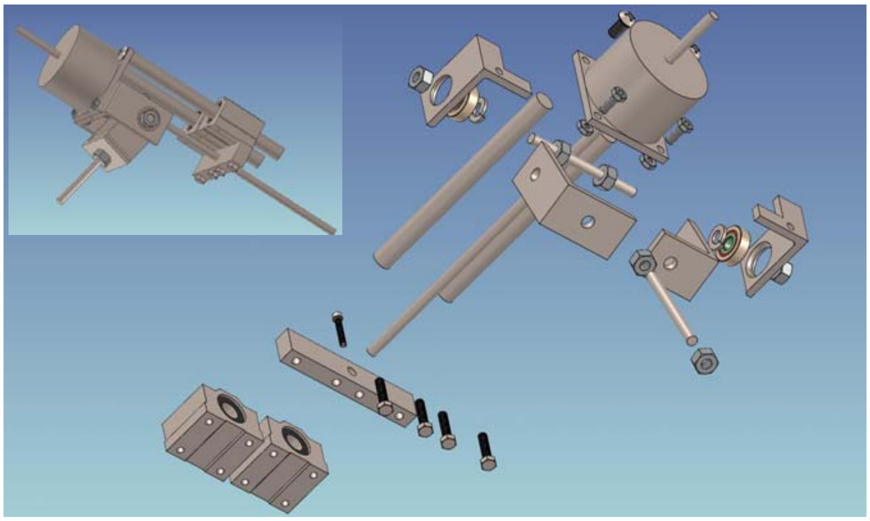


Figure 5: The design of a length-changeable strut.

The detail design of a length-changeable strut based on a linear motor is further shown in Figure 5. For the linear actuator, it creates linear motions only when the end of the lead screw has a holding torque. To impose the required torque, we use a pair of slide bushings with two guide rails on each motor. Our design has good modularity since all the struts in the designed system are exactly the same.

Table 1 is the expense of the components that are used in the prototype system. The total cost is less than $1,500 excluding the base frame. Compared to the commercial hexapod machines, it has a rather low cost and has the potential to be used in developing low-cost 3D printers with multi-directional motions. The 6-axis motion system is general. Various accumulative tools can easily be integrated in the system. Both the FDM and CNCA processes are demonstrated using the developed prototype system. In addition, since all the motions are conducted by moving the accumulative tools, the system can have low inertia with small energy consumption.

Table 1: Cost of the prototype system

Item	Quantity	Price each
Linear actuator	6	$75
Aluminum plate	4"×4", 12"×24"	$78
Aluminum angle	4 '	$32
Bearing	24	$7.0
Lead screw	6	$10
3"alloy steel thread stud	12	$1.5
Ball joint	6	$7.0
Aluminum rod	6'	$10
Others (screw, nuts, slide, bushing, etc.)	NA	$80
Motor controller	1	$500
Total	**NA**	**$1,438**

3 Motion Planning and Software System Design

The desired tool motion in the 6-axis parallel kinematic machine needs to be converted into the linear motions of the six length-changeable struts. Accordingly the motion controller can be used to control the linear actuators to move the required displacements.

3.1 System Coordinate Transformation

In the motion planning, we use quaternion q to describe the pose of the moving platform. That is, for a rotation angle θ around a unit vector $(v_x, v_y, v_z)^T$, its quaternion q is described as:

$$q = (q_1, q_2, q_3, q_4)^T = (v_x \sin(\frac{\theta}{2}), v_y \sin(\frac{\theta}{2}), v_z \sin(\frac{\theta}{2}), \cos(\frac{\theta}{2}))^T \quad (1)$$

Accordingly the rotation matrix can be obtained using quaternion elements:

$$R(q) = \begin{pmatrix} q_1^2 + q_2^2 - q_3^2 - q_4^2 & 2q_2q_3 - 2q_1q_4 & 2q_2q_4 + 2q_1q_3 \\ 2q_2q_3 + 2q_1q_4 & q_1^2 - q_2^2 + q_3^2 - q_4^2 & 2q_3q_4 - 2q_1q_2 \\ 2q_2q_4 - 2q_1q_3 & 2q_3q_4 + 2q_1q_2 & q_1^2 - q_2^2 - q_3^2 + q_4^2 \end{pmatrix} \quad (2)$$

To establish the transformation model from the given quaternion to the absolute displacement of the six axes, two coordinate systems are shown in Figure 6. One coordinate system is attached to the fixed base frame (*B*) and another one is fixed on the moving frame (*P*). Initially, the moving frame has the same coordinate axes as those of the base frame (refer to $\boldsymbol{O_P}$ and $\boldsymbol{O_B}$ in the figure). During the fabrication process, the coordinate system of the moving frame is aligned with the accumulation tool and will be different from the original one.

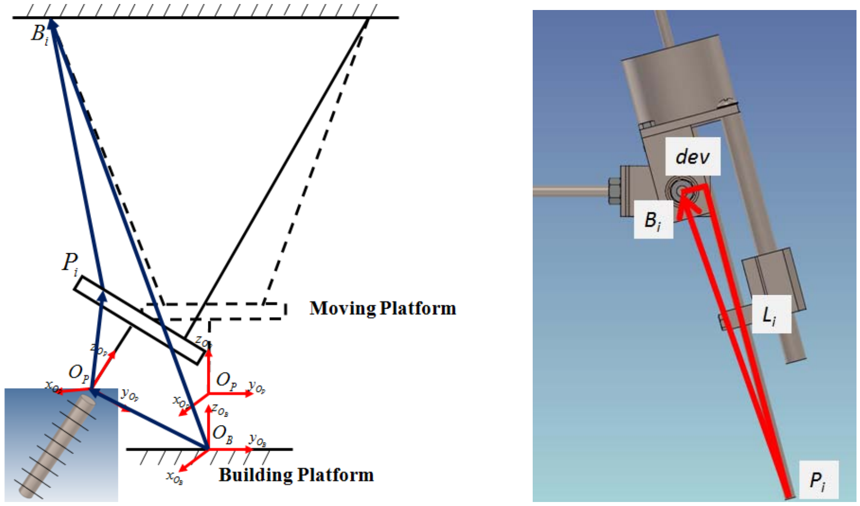


Figure 6: An illustration of the coordinate systems and main parameters of the prototyping system.

Suppose any platform pose is given as $(x_{o_P}, y_{o_P}, z_{o_P}, q)$. Its first part, $(x_{o_P}, y_{o_P}, z_{o_P})$, is the origin position of the moving frame. The second part, q, is the quaternion of the moving frame after the rotation from its initial position. Both of them are defined in terms of the coordinate system of the base frame. Accordingly we know:

$$\overrightarrow{P_iB_i}^B = \overrightarrow{O_BB_i}^B - \overrightarrow{O_BO_P}^B - R \bullet \overrightarrow{O_PP_i}^P \tag{3}$$

where $\overrightarrow{P_iB_i}^B$ is the vector $\overrightarrow{P_iB_i}$ defined in the coordinate system of the base frame B; $\overrightarrow{O_BB_i}^B$ is the position of the universal joint B_i in terms of the coordinate system of the base frame; $\overrightarrow{O_BO_P}^B$ is the position of the tool tip; $\overrightarrow{O_BO_P}^B = (x_{o_P}, y_{o_P}, z_{o_P})$; $\overrightarrow{O_PP_i}^P$ is the position of the ball joint in the moving frame; R is the rotation matrix that is calculated by equation (2); and i= 0, 1,..5. Consequently the displacement Δl_i of the i^{th} strut is:

$$\Delta l_i = \left\| \overrightarrow{P_iB_i}^B \right\| - l_{i0}$$

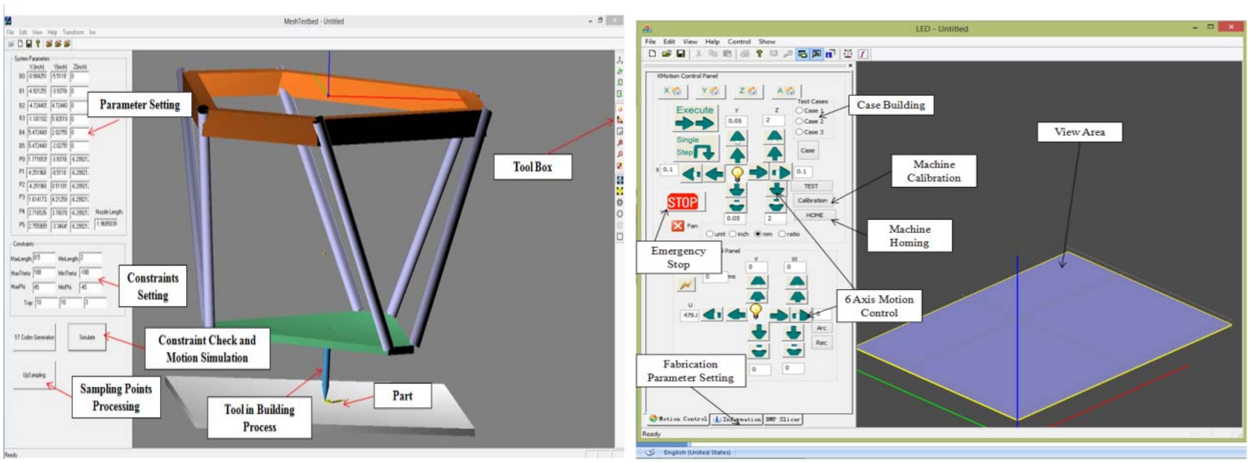
where l_{i0} is the initial joint offset.

In our hardware design, the base joints are not exactly located on the legs. Consequently the deviation of the lead screw from the base joint needs to be considered when computing the displacement. That is,

$$\Delta l_i = \sqrt{\left\| \overrightarrow{P_iB_i}^B \right\|^2 - dev^2} - l_{i0} \tag{4}$$

4.2 Movement Simulation

A simulation software system was developed for computing the tool path based on Equations [1]-[4]. Figure 7.a shows the Graphical User Interface (GUI) of the developed simulation software system. A G-code file with defined quaternion at each point can be opened in the view area. The position of each joint can be set in the left panel. The parameters values are set based on the machine calibration, which will be discussed in Section 5. Before the simulation, an axis motion command file will be generated from the G-code file to define quaternion based on Equations (3) and (4). The simulation starts when the axis motion command file passes the constraint check. After that, the final file will be sent to the motion control software system, whose GUI is shown in Figure 7.b. Accordingly, the 6 linear motors will be controlled with the defined moving positions and speeds.



(a) The simulation software system (b) The motion control software system

Figure 7: Software systems developed for the parallel kinematic machine.

4 Platform Calibration

A set of 42 parameters including $\overrightarrow{O_B B_i}^B$, $\overrightarrow{O_P P_i}^P$ and l_{i0} (i=1~6) need to be set in the coordinate transformation models as described in Equations (3) ~ (4). The calibration of these parameter values is necessary for more accurate control of the 6-axis motion. The calibration approach that is used in our system is to iteratively update the system parameters by an error model such that a defined cost function can be minimized based on the given orientation and translation of the moving platform. The calibration approach is presented in more details as follows.

4.1 Cost Function and Error Model

A cost function for the 6-axis platform calibration is defined in [19]. It uses strut length measurement residual at all measured poses as the objective function. And the calibration problem can be formulated as a nonlinear optimization problem, which is given as follows:

$$\text{Minimize: } C = \sum_{j=1}^{n}\sum_{i=1}^{6} s_{ij} \tag{5}$$

$$s_{ij} = (l_{i0} + \Delta l_{ij})^2 + dev^2 - (\overrightarrow{O_B B_i}^B - \overrightarrow{O_B O_P}^B - R \bullet \overrightarrow{O_P P_i}^P)^T (\overrightarrow{O_B B_i}^B - \overrightarrow{O_B O_P}^B - R \bullet \overrightarrow{O_P P_i}^P)$$

i=1,2,…,6; j=1,2,…,n

where n is the number of calibrated poses, and Δl_{ij} is the input moving displacement of the i^{th} linear actuator at the j^{th} calibrated pose of the platform.

From the kinematic equations (3) and (4), we could get an error model in the form:

$$s_{ij} = J \bullet \Delta\rho \tag{6}$$

where J is the Jacobian matrix, $\Delta\rho = [d\overrightarrow{O_B O_P}^B \;\; d\overrightarrow{O_P P_i}^P \;\; dl_i]^T$.

With the cost function and the error model, the nonlinear optimization function can be solved by *Gauss-Newton* Algorithm.

4.2 Measurement of Platform Poses

A set of sufficient number of platform poses need to be collected in order to calibrate the machine using Equation (5). Since 42 system parameters are unknown in the axis displacement generation model, the measurement of seven or more poses are required. In our experiments, we randomly chose twelve poses, twice the minimum number of poses, to ensure the accuracy of the calibrated parameter values.

A computer vision based method is used in measuring the tool tip position and orientation. As shown in Figure 8, two cameras are positioned orthogonal to each other. Three targets were placed on the moving platform. Target 1 is located at the tool tip. Targets 2 and 3 were symmetric about the X axis of the moving frame. Each camera is calibrated such that the 3D point positions of the targets can be computed based on the captured 2D images of both cameras. Accordingly, the rotation matrix of the moving frame can be derived by the SVD method based on the positions of the three targets. The process is described in more details as follows.

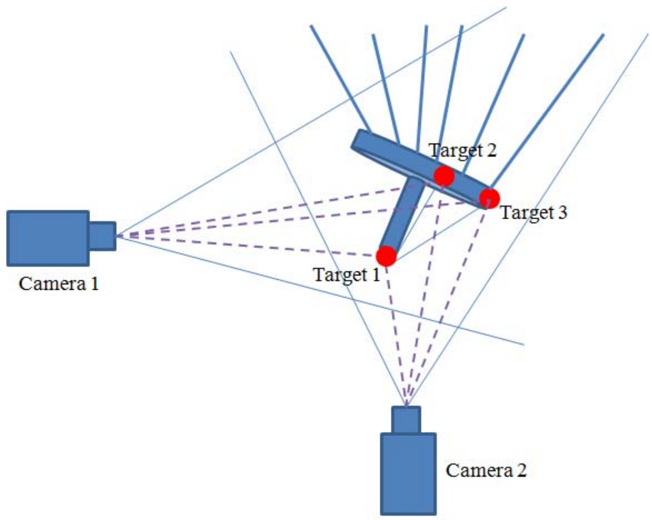


Figure 8: An illustration of the platform pose measurement using two cameras.

4.2.1 Camera Calibration

The two cameras are first calibrated in order to identify the relation between a pixel on a 2D image and its corresponding 3D position. Considering the nonlinearity of a camera, we equally divide the working volume into 11 layers along the X and Y axes for camera 1 and 2, respectively. The distance between two neighboring layers is 5mm. A printed chessboard is placed at each layer; an image will be taken to analyze all the corner points of the chessboard. Since the coordinates of each corner point on the chessboard are known, a database of the relations between an image pixel and its base frame coordinate at each layer can be established. For example, suppose the i^{th} corner point on the chessboard at layer j in camera 1's calibration volume has world coordinate ($x_{ij}^1, y_{ij}^1, z_{ij}^1$). After its pixel ($x_{image}, y_{image}$) in the image is identified, a database for camera 1 can be obtained in the form of ($x_{ij}^1, y_{ij}^1, z_{ij}^1, x_{image}, y_{image}$). Inversely, if pixel position of a point on the image is given as (x_{image}, y_{image}), its corresponding 3D position at layer j can be calculated through the bilinear interpolation of the four corners of the checker box in which the pixel falls.

4.2.2 3D Point Coordinate Computation

For a certain platform pose, the three targets on the moving platform can be captured by the two cameras (refer to Figure 9). Accordingly, two groups of pixel positions (x_{image}^1, y_{image}^1) and (x_{image}^2, y_{image}^2) from cameras 1 and 2 can be recorded for any target. Since the depth of the target in the camera's view volume is unknown, we can calculate its 3D position at each layer first. For example, the world coordinates $P_{1,0}$ can be retrieved from the database related to pixel (x_{image}^1, y_{image}^1) at layer 0. Similarly all these 3D coordinates identified at each layer will form a distorted camera view line (refer to Figure 9).

For the same target, the two camera lines may not exactly intersect due to the camera calibration errors. Instead, the 3D coordinate of the target can be computed as the point with the minimum distances to both camera lines. For example, the closest distance between the two camera lines as shown in Figure 9 is between segment $P_{1,1}P_{1,2}$ and segment $P_{2,5}P_{2,6}$. Such an approach was also used in [20].

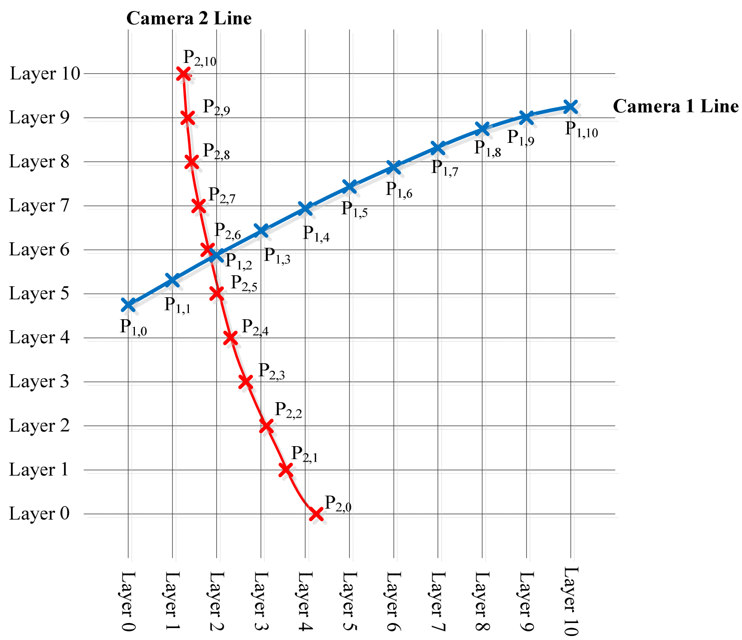


Figure 9: Point retrieval by calculating the closing point between two camera lines.

5 Multi-directional AM Process Overview

Based on the developed low cost parallel kinematic machine, the major steps of a multi-directional AM system include (1) tool path generation, (2) system coordinate transformation, (3) platform constraint checking, (4) movement simulation, and (5) part fabrication. In the tool path generation, an input CAD model is sliced in desired building orientation. The slicing direction can be determined based on surface normal or feature skeleton. A sliced layer contour can be sampled into a set of discrete points. Each sampling point can be used to compute the positions of the six linear actuators. At each point, the tool position and orientation are given. As discussed in Section 3, the 3D coordinate of the tool along with its accumulation orientation is converted into a transformation model to compute the related distances L_0-L_5 for the six struts of the machine. The displacement vector can then be sent to the motion controller to achieve the desired platform pose.

Note that not all the vectors computed based on the transformation process can be achieved by the prototype system. Several constraints exist including the limitation of actuators' stroke (i..e [L_{min}, L_{max}]), the limitation of the range of the passive joint, and the minimum distance between each actuator's lead screw. Hence the computed results need to be checked using the known constraints. The tool path can be simulated in our software system to verify whether the 6-dimensional motion vectors satisfy all the constraint equations. Finally, the verified 6 dimension coordinate vectors (L_0, L_1, L_2, L_3, L_4, L_5) can be sent to the control system to start the building process.

Figure 10 shows the data processing pipeline of the developed multi-directional AM system. A CNC control software system (e.g. Mach 3) can be used in converting a given CAD model into numeric control G-codes. The generated G-codes have only the coordinate positions along which the tool tip will travel. The tool can be positioned at various orientations for a given position in the G-code. One good candidate is to align the tool orientation with the related part surface normal.

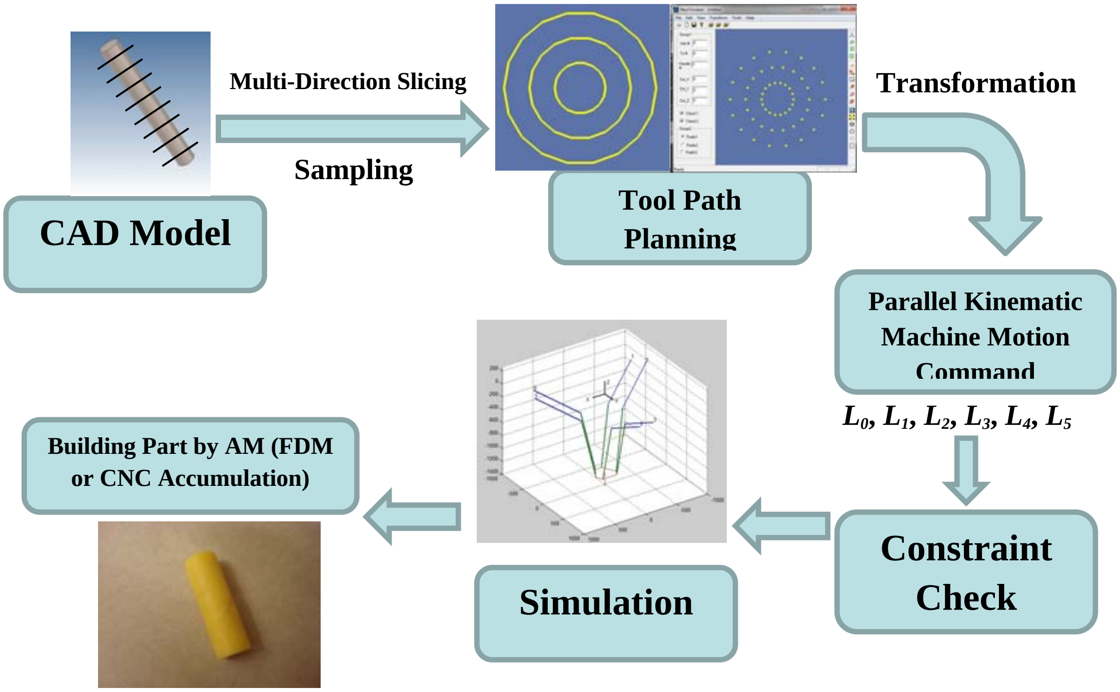


Figure 10: Data processing pipeline of the multi-directional AM systems using the parallel kinematic machine.

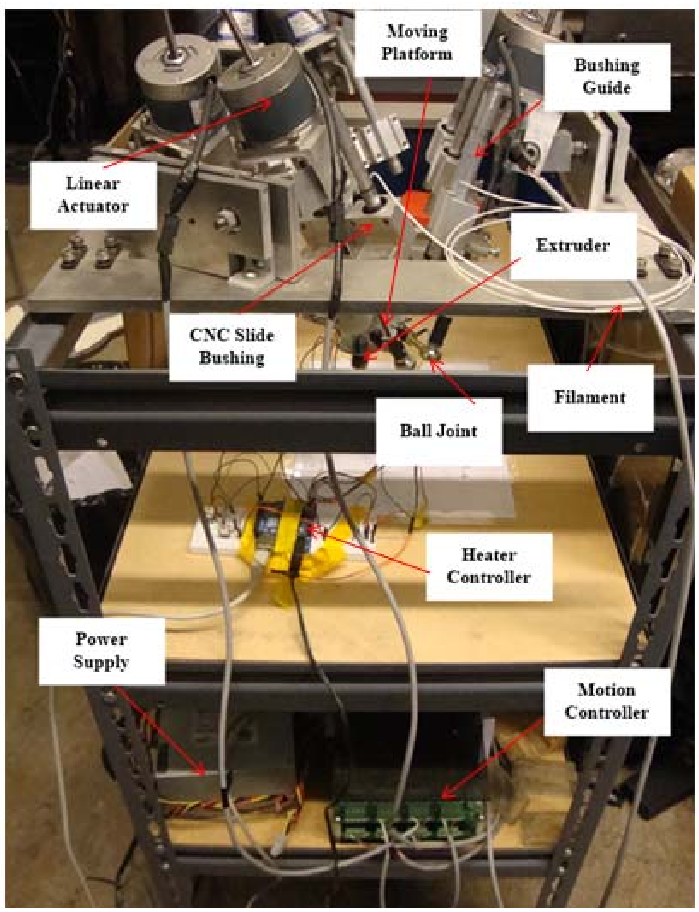


Figure 11: The prototype system for the multi-directional FDM process.

6 Experimental Tests

The developed parallel kinematic machine can be used in various multi-directional AM processes such as the FDM or CNC accumulation processes. A photo of the developed prototype system with a filament extruder of the FDM process is shown in Figure 11. In this section, some of the test cases we performed are presented to demonstrate its capability.

In the first test case, a CAD model as shown in Figure 12.a is to be fabricated. The planned tool paths are shown in Figure 12.b. Note that the surface normal of the shape changes from the vertical direction $\boldsymbol{n_1}$ to $\boldsymbol{n_2}$. For the horizontal portion of the model, $\boldsymbol{n_1}$ is chosen as the building direction. For the slope portion of the model, $\boldsymbol{n_3}$ is chosen as the building direction for better attachment to the previously deposited layers. Figure 13 shows the building results by using the multi-directional FDM system. The melted filament can attach well to the former solidified layers. Hence the slope portion can be built without any supports by using the material deposition direction of $\boldsymbol{n_3}$ instead of $\boldsymbol{n_1}$.

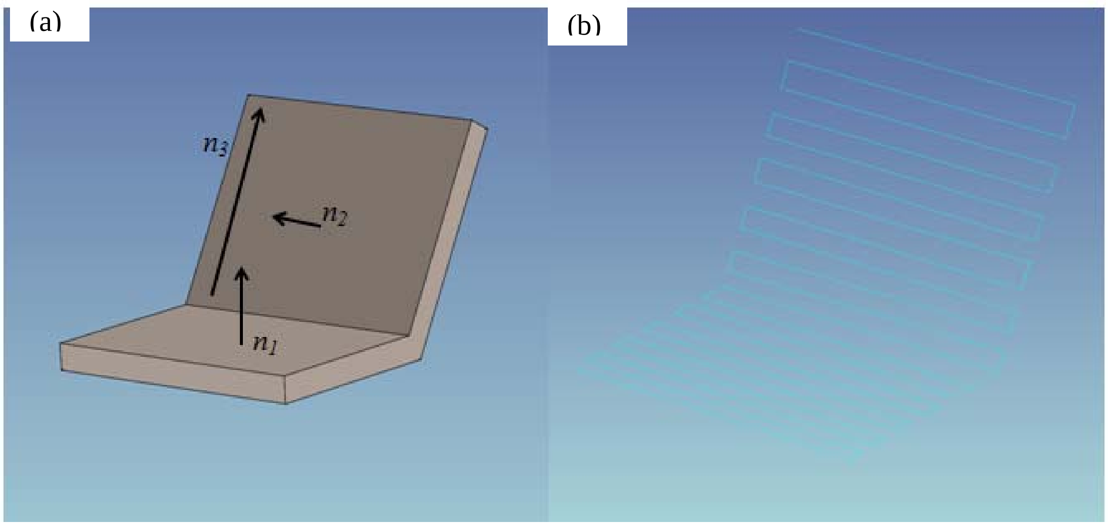


Figure 12: A model with an inclined plane to be built. (a) Different building directions; (b) planned tool path.

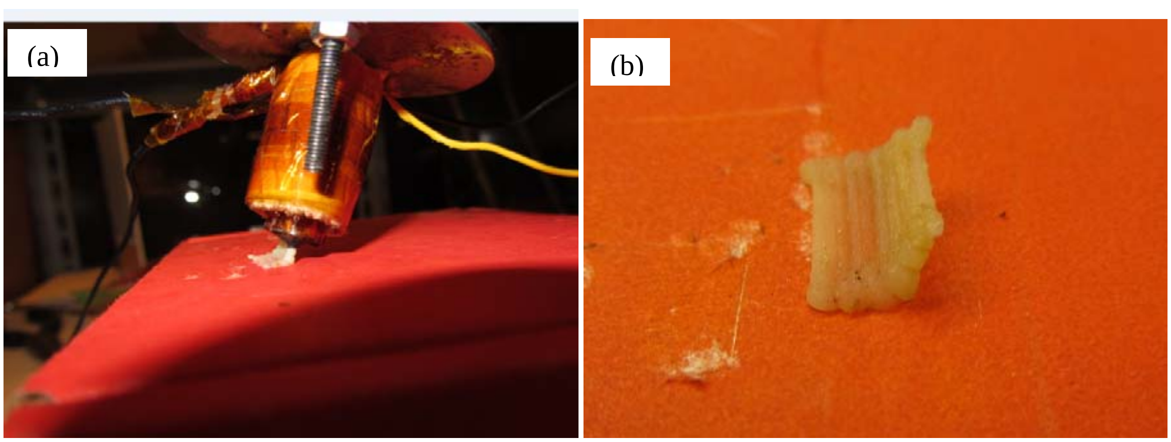


Figure 13: Test results. (a) Part fabrication by FDM extrusion in a tilted angle; (b) built part.

In the second test case, three characters "USC" are to be built on a tilted plane as shown in Figure 14.a. In the linear motion based FDM machines, a nozzle can only extrude filaments vertically. Hence it would be difficult to build features on a tilted plane since a large gap will exist between the tilted plane and the vertical nozzle in order to avoid the collision between them. In comparison, a desired gap distance can be achieved by rotating the nozzle to be perpendicular to the plane. Accordingly the characters can be fabricated on the tilted plane, which are shown in Figure 14.b.

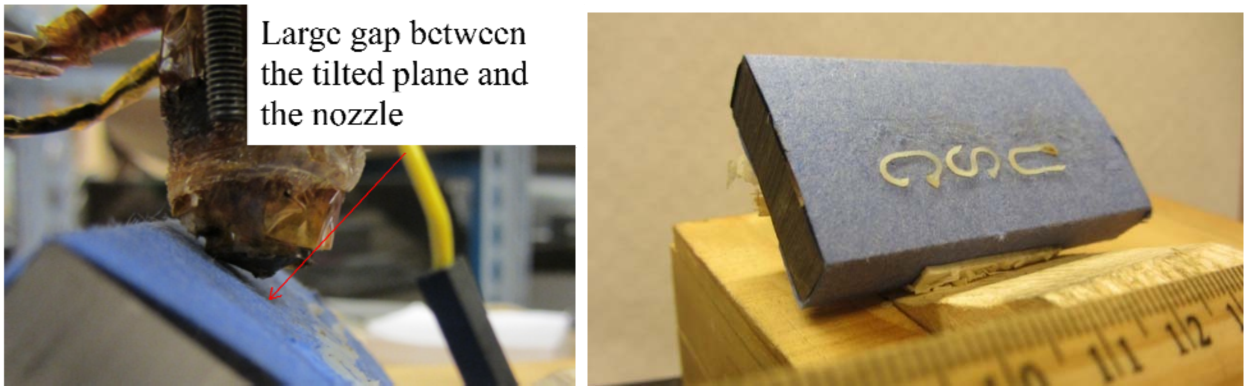


Figure 14: Test results. (a) Problem with the vertical building on a tilted plane; (b) built characters on the plane.

The third case is to deposit a curved line on the surface of a bottle. As shown in Figure 15, the bottle body is a cylinder with a diameter of ~31mm. In order to build a curved line along its surface, the nozzle direction needs to be constantly changed in order to keep the tool to have a building direction that is coaxial with the surface normal. The nozzle orientations at the start and end positions are shown Figure 15.a. The angles of the nozzle will change from -20º to +20º during the building process. Figure 15.b shows the fabricated result.

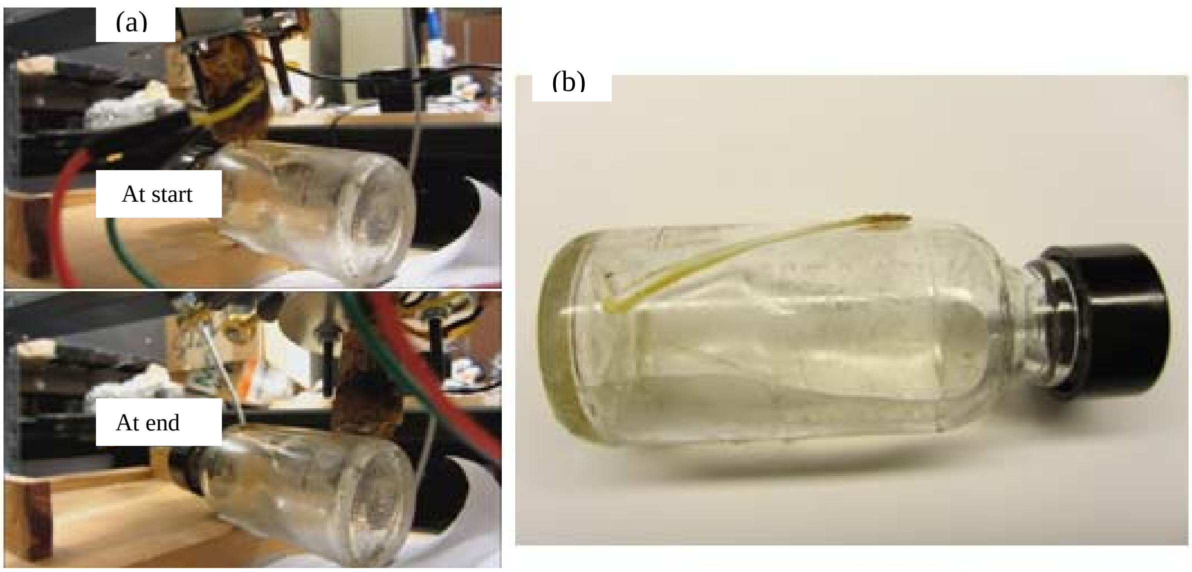


Figure 15: Test results. (a) FDM nozzle at different positions; (b) built result on the curved surface.

A youtube video of the developed multi-directional AM system and the related experimental tests can be found at [21].

7 Conclusion and Future Work

In the paper, a low-cost 6-axis motion system based on the Stewart mechanism has been developed for multi-directional additive manufacturing. Our design is modular and can easily be incorporated with various accumulative tools. In addition, the system based on six linear actuators is relatively inexpensive. It can move tools in satisfactory speed. By enabling full 6-axis motions between a tool and a work piece, an AM system can deposit materials from multiple directions. We further demonstrated that the drawbacks associated with the layer-based AM processes such as the limitations on building-around-inserts can be overcome by the multi-directional AM processes.

The specifications of our 1st generation multi-direction AM machine are:

(1) Working volume. The working volume of our system is designed as 300mm×300mm×150mm. The working volume depends on the travel range of the lead screws and slide bushings, as well as the angle range of the ball joints.
(2) Accuracy. The accuracy of the prototype system is <0.5mm when the tool direction remains the same, e.g. building planar features on a tilted plane; however, the error can be larger when the tool direction keeps changing, e.g. building features on a curved surface. A main reason is the poor calibration resolution we used (11 planes were used with a layer distance of 5mm). Another possible improvement is to improve motion planning algorithm and the hardware construction.
(3) Rotation angle of the platform. The rotation angle of the moving frame in our prototype system is ±30º. Like the working volume, the rotation range is mainly dependent on the selected ball joints, and the ravel ranges of lead screws and slide bushings.

We plan to further improve the accuracy of the prototype system by better software and hardware implementation, and more precise calibration. In addition, test cases for applications such as part repairing and building around inserts will be further studied.

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Reference

[1] Y. Pan, X. Zhao, C. Zhou, Y. Chen. Smooth Surface Fabrication in the Mask Projection based Stereolithography. SME Journal of Manufacturing Processes, Vol. 14, No. 4, pp. 460-470, 2012.

[2] Sager B. SLA characterization for surface finish improvement: Inverse design methods for process planning [dissertation]. 2006.

[3] Benay Sager, David W. Rosen. Use of parameter estimation for stereolithography surface finish improvement. Rapid Prototyping Journal. Vol.14, No. 4, 213-20, 2008.

[4] Pandey PM, Venkata Reddy N, Dhande SG. Improvement of surface finish by staircase machining in fused deposition modeling. Journal of Materials Processing Tech. Vol. 132(1):323-31, 2003.

[5] Mason A. Multi-axis hybrid rapid prototyping using fusion deposition modeling [dissertation]. ; 2006

[6] Narahara, H. and Saito, K. Study on the improvement of surface roughness of complex model created by three dimensional photofabrication – proposal of lift up irradiation method, Journal of the Japan Society for Precision Engineering, Vol. 61, No. 2, pp. 233-7, 1995.

[7] Alok Kataria, David W. Rosen. Building around inserts: Methods for fabricating complex devices in stereolithography. Rapid Prototyping Journal. Vol. 7(5): 253-62, 2001.

[8] Ruan J, Eiamsa-ard K, Liou FW. Automatic process planning and toolpath generation of a multiaxis hybrid manufacturing system. Journal of Manufacturing Processes. Vol. 7(1):57-68, 2005.

[9] P Singh, Y Moon, D Dutta, S Kota. Design of a customized multi-directional layered deposition system based on part geometry. In: Proceedings of the 14th Solid Freeform Fabrication Symposium, Austin, TX, pp. 266-278, 2003.

[10] McLean, Marc A; Shannon, G. J; Steen, William M. Laser generating metallic components. Proceedings of SPIE, ISSN 0277-786X, Volume 3092, Issue 1, 1997.

[11] J.Kim. Advanced multi-directional UV lithography for three dimensional (3-D) micro/nano structures. Doctor of Philosophy Dissertation. University at Buffalo, the State University of New York, 2011.

[12] A.J.Pinkerton, W.Wang, L.Li. Component repair using laser direct metal deposition. J.Engineering Manufacture. Vol.222: 827-836, 2008.

[13] B.Dutta, S.Palaniswamy, J.Choi etc.Additive Manufacturing by Direct Metal Deposition .Advanced Materials & Processes. Vol. 5: 33-36, 2011.

[14] J.Choi, Y.Chang. Analysis of Laser Control Effects for Direct Metal Deposition Process. Journal of Mechanical Science and Techonology (KSME Int.J.). Vol.20, No.10, pp. 1680-1690, 2006.

[15] B.Dutta, V.Singh, H.Natu, etc. Six-axis direct metal deposition technology enables creation/coating of new parts or remanufacturing of damaged parts with near net-shape. Advanced Materials & Processes. Vol. 3, pp.29-31, 2009.

[16] J.Ruan, L.Tang, F.W.Liou, etc.. Direct Three-Dimensional Layer Metal Deposition. Journal of Manufacturing Science and Engineering. Vol. 12, 064502-1~064502-6. 2010,

[17] J.O.Milewski, G.K.Lewis, D.J.Thoma, etc.. Directed light fabrication of a solid metal hemisphere using 5-axis powder deposition. Journal of Materials Processing Technology. Vol. 75, pp. 165-172, 1988.

[18] Y. Chen, C. Zhou, J. Lao. A Layerless Additive Manufacturing Process based on CNC Accumulation. Rapid Prototyping Journal, 2011.

[19] H. Zhuang, J. Yan and O. Masory. Calibration of Stewart Platforms and other Parallel Manipulators by minimizing Inverse Kinematic Residuals. Journal of Robotic Systems.395-405, 1998.

[20] X. Zhao, Y. Pan, C. Zhou, Y. Chen, C. C. L. Wang. An Integrated CNC Accumulation System for Automatic Building-around-inserts. SME Journal of Manufacturing Processes, Vol. 15, No. 4, 2013.

[21] X. Song, Y. Pan and Y. Chen, retrieved Sept.22, 2013, http://www.youtube.com/watch?v=qGyiXFGvkqE.