Design of a customized multi-directional layered deposition system based on part geometry.

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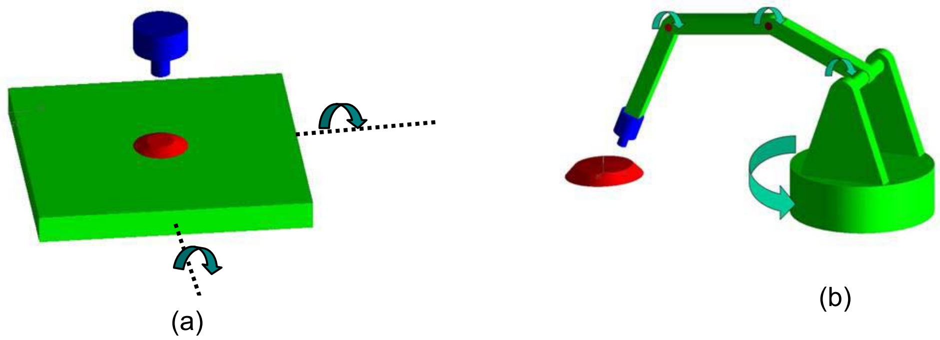
Abstract

Multi-Direction Layered Deposition (MDLD) reduces the need for supports by depositing on a part along multiple directions. This requires the design of a new mechanism to re-orient the part, such that the deposition head can approach from different orientations. We present a customized compliant parallel kinematic machine design configured to deposit a set of part geometries. Relationships between the process planning for the MDLD of a part geometry and considerations in the design of the customized machine mechanism are illustrated. MDLD process planning is based on progressive part decomposition and kinematic machine design uses dual number algebra and screw theory.

1. Introduction

The past decade has seen the development of numerous Layered Manufacturing (LM) techniques. The main advantage afforded by LM is its ability to produce geometrically complex parts without specialized tooling in a relatively short period of time. LM processes are characterized by the need for sacrificial structures to support overhanging regions of the part. This necessitates time consuming post-processing and degrades part quality.

Multi-Direction Layered Deposition (MDLD) Systems such as [3][4][5][7] build parts without supports by depositing a part along multiple directions. Depending on the process, either the deposition nozzle or the base table has multi-axis kinematics (refer Figure 1).


(a)

(b)

Figure 1: (a) Deposition Table with rotational and translational actuation (b) Deposition nozzle mounted on a multi-axis robotic arm.

This necessitates a mechanism with more than 3 degrees of freedom. A full 6 degree of freedom mechanism is expensive and is very often redundant for customers engaged in the design and fabrication of specific geometries. Recognizing this, recent research efforts such as [8][15] have proposed simplified kinematics for multi-direction deposition systems. While they have a distinct advantage over 2.5D LM systems, the fixed configuration of the nozzles/deposition table restricts support-less deposition to a few part geometries.

In this research we propose a cost effective method to achieve multi-direction deposition by using kinematics which are customized to fabricate a specific family of parts.

For a given geometric part family, our approach comprises of two tasks. The first task is the process planning underlying multi-direction layered deposition of a given member of the part family. The input part geometry is converted into sets of uniform parallel slices aligned along a set of vectors called the *build directions*. In the second task, slice geometry and build directions are used to derive the machine kinematics. Traditionally mechanism design has been a mixture of art and science. Researchers in the past have tried to classify, compile and codify basic elements of mechanisms in order to systematize the creative design process. In this research, we propose a compliant parallel kinematic machine (CPKM) design methodology [9][10]. The CPKM methodology synthesizes the mechanism using dual number algebra and screw theory. The synthesized mechanism has high accuracy because it uses compliant joints which are clearance and friction free mechanical component. A typical CPKM mechanism is shown in Figure 2.

Figure 2: A deposition table constructed using the Compliant Parallel Machine Design Methodology

The remainder of the paper is organized as follows: Section 2 details the process planning methodology underlying the MDLD of a part. Section 3 presents a brief summary of the theory underlying CPKM and its relevance in the context of MDLD. In Section 4 we define an illustrative parametric part family along with its MDLD process planning. The output of the process planning information is used in

Section 5 to construct the kinematics of a CPKM. Section 6 concludes the paper with a summary of the research and directions for future research.

2. Process Planning Methodology for MDLD

A process planning framework for MDLD was proposed in an earlier publication [11]. It was assumed that the deposition nozzle is mounted on a multi-degree of freedom robotic arm. No other assumptions were made about the kinematics of the MDLD system. In [11] we addressed the core question in the analysis of multi-direction deposition systems, which is: how much of the part should be built in one direction and why? A brief overview of the process planning tasks is covered in this section. The reader is referred to [11] and [12] for further details.

Assuming that the initial orientation of the part is user defined, the following MDLD process planning tasks were identified:

1. Decomposition of the part volume.
2. Establishing the Build Directions.
3. Sequencing the Decomposed sub-volumes.

The overall strategy for multi-direction slicing involves the progressive decomposition of the part (*P*) into sub-volumes each of which can be completely built along a certain direction. The input to each stage of this progressive decomposition is an unprocessed sub-volume (V_{unproc}) of the part which is processed using two operations:

1. Find a build direction, $\overline{B}$.
2. Using $\overline{B}$ to decompose V_{unproc} into buildable and unbuildable sub-volumes.

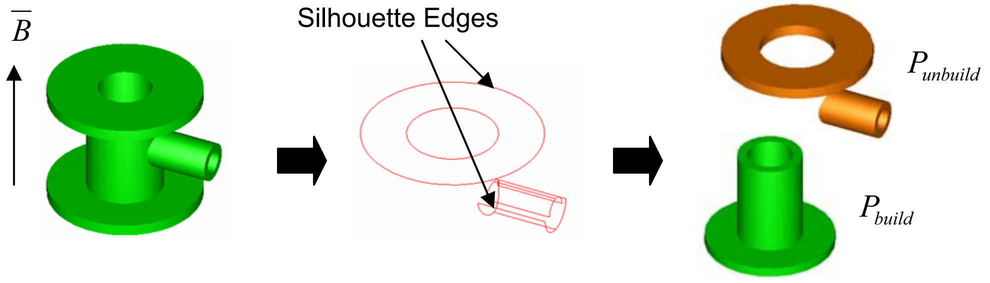
The buildable part of V_{unproc} is classified as a processed sub-volume (V_{proc}) with $\overline{B}$ as its assigned build direction. The unbuildable sub-volume (V_{unproc}) forms the input to the next stage of the decomposition process. This stage-wise decomposition stops when:

$$\bigcup_i V_{proc_i} = Vol(P)$$

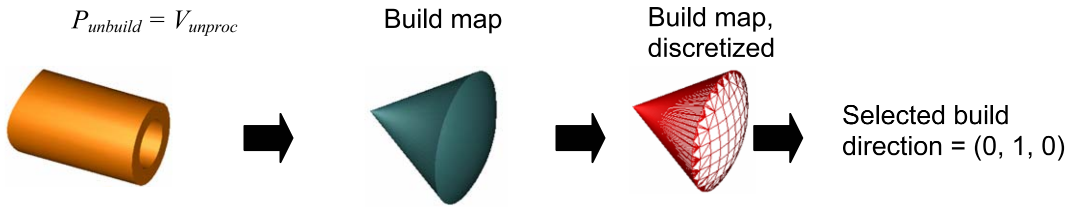
Where *Vol(P)* is the volume of the part *P*.

2.1. Part Volume Decomposition

The overhang angle constraint as defined by Allen and Dutta [2] restricts the deposition of overhanging regions in LM. For a given build direction ($\overline{B}$), the part volume decomposition algorithm is concerned with the identification and disjunction of part volumes which can be built and those which cannot. The algorithm defines surface regions to be unbuildable when the angle between the surface normals and the build direction is greater than 90 degrees. Such unbuildable surface regions are bounded by *silhouette edges* of the surface [6] when viewed from $-\overline{B}$, the opposite of the assigned build direction. Unbuildable part volumes are then identified by sweeping the unbuildable surface regions along $\overline{B}$ and subtracting the resulting swept volume from the part P. This is shown through an illustrative CAD model below (ref. Figure 3).



(a) Part Volume Decomposition



(b) Build Direction Determination

Figure 3: Part volume decomposition and build direction determination for MDLD.

2.2. Build Direction Determination

In this task a build direction is assigned to an unprocessed sub-volume. It involves both the identification of all feasible build directions and the selection of the best build direction. Any vector which makes an angle of 90 degrees or lesser with all surface normals of the part boundary is considered to be a feasible build direction. The set of all feasible build directions is called the *build map*. The best build direction (a member of the build map) minimizes the average weighted cusp height as defined by Alexander and Dutta in [1]. An illustrative build map of a part volume and the selected build direction for a CAD model is shown in Figure 3b.

2.3. Volume Sequencing

Layered deposition requires the presence of a base substrate. Using Figure 3a as a reference, P_{build} must be deposited before $P_{unbuild}$ since the base or the common face between the two sub-volumes lies on P_{build}. Consequently the deposition of $P_{unbuild}$ cannot start till its base has been created, establishing P_{build}'s precedence in the deposition sequence.

The overall process planning algorithm for MDLD is summed up in the following flowchart (ref. Figure 4). As mentioned, the orientation of the part relative to the deposition table, i.e. the initial build direction ($\overline{B}$) is user defined. The build direction determination module and volume decomposition are applied recursively till the entire part is decomposed. These are succeeded by Part volume sequencing and slicing along assigned build directions ($\overline{B}$).

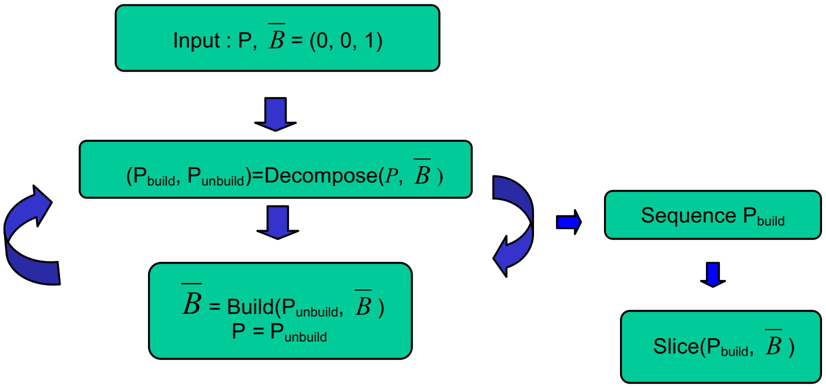
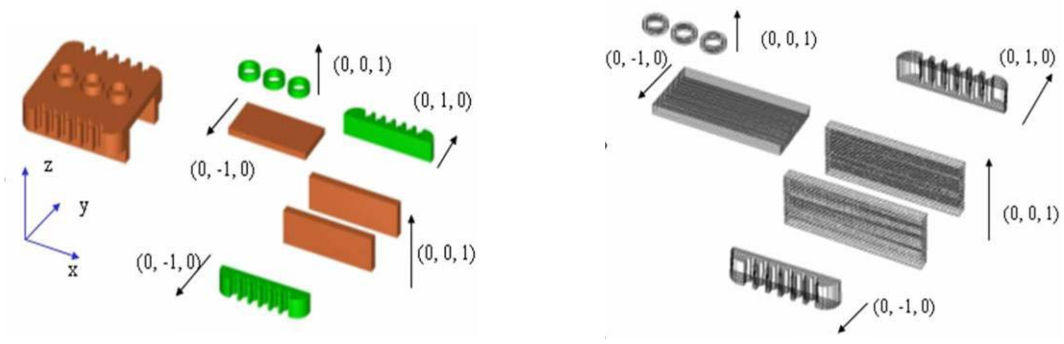


Figure 4: Overall algorithm for MDLD process planning

An illustrative CAD model with its volume decomposition is shown in Figure 4a. The model is consequently sliced as shown in Figure 4b. The initial build direction is chosen along the Z^+ axis.



(a)
(b)

Figure 3: (a) A CAD model with its MDS decomposition and associated build directions (b) Slices of MDS subvolumes along selected build directions.

3. Mechanism Synthesis

A machine for MDLD is comprised of two parts; 1) X-Y printing overhang head unit, and 2) the workpiece orientation unit. Generic LM machines have an X-Y printing unit that has coordinated control in the X-Y direction and a separate control for the Z direction. To design the MDLM machine, we need to add the workpiece orientation unit that aligns the building direction to the Z axis of the head unit. This paper presents the design of the workpiece support unit that is using the compliant mechanisms.

Traditional mechanisms attain motion through the use of rigid links and discrete joints. They are ubiquitous in the world of machines and have been studied for centuries. Within the last several decades, there has been a growing interest in what have been termed compliant mechanisms. Unlike their rigid body counterparts, compliant mechanisms utilize the flexibility of their members to transmit or transform motion and forces. While traditional mechanisms are designed to be stiff and strong, compliant mechanisms are designed to be flexible and strong.

Not every problem is best solved with compliant mechanisms, but for applications better suited for compliant mechanisms, there are a number of significant benefits. They can be summarized as follows:

- *Assembly*: Compliant mechanisms are designed to be monolithic. Thus, there is a reduced need for mechanism assembly. In most cases, compliant mechanisms are designed to be coupled with actuators. This typically requires some assembly, but the number of parts is far less in comparison to traditional mechanisms.
- *No wear*: Compliant mechanisms attain mobility through deformation, and therefore do not experience wear. As such, there is a reduced need for maintenance such as lubrication. Also, failure occurs either from static or fatigue failure. These types of failure are more predictable than wear phenomena.
- *No backlash*: Due to the absence of discrete joints, compliant mechanisms do not suffer from backlash. As a result, high precision may be attained.
- *Energy storage*: Compliant mechanisms store elastic energy as they deform. This energy may be used to assist in applications requiring a return stage. There is a reduced need for springs and possible actuation.

The design of multi-degrees of freedom mechanism is not always been a simple task while maintaining the accuracy and stiffness of the mechanisms. One of the most popular design of spatial multi degrees of freedom mechanisms is parallel kinematic machines (PKM) which is know to have high stiffness. However, PKM has poor accuracy compare to the serial mechanisms and planar mechanisms since it needs more mechanical joints than the other mechanisms. In this paper, we are using the compliant joint [9] based parallel kinematic machines; CPKM (Compliant Parallel Kinematic Machines) so the mechanism has high stiffness without the accuracy problems.

The mechanism does not need the full six degrees of freedom since CPKM is customized around a parametric part family. In this paper, we take the building block approach to design a CPKM with less than six degrees of freedom [10].

CPKM is comprised of a top plate (end effector or work holding), a bottom plate, a constraining leg and active legs. The top plate holds the workpiece and the bottom plate is attached to the MDLM machine. The constraining leg is a one serial kinematic chain that connects those two plates and defines the total degrees of freedom of the workpiece supporting unit. The active legs are attached after the constraining leg is configured so that the machine can be activated.

To design CPKM, its requirements should be clarified first. The requirements for a CPKM are the required motions. To capture the characteristics of the motions, screw theory based dual vector representation and its algebra has been used in this research. When we think of a motion, it includes many aspects of the motion such as range of motion, type of motion, direction of motion and location of motion. The dual vector representation is one of the most suitable methods to represent these in explicit form. The algebraic operations and modeling methods used in this research is following reference [9].

The format of the dual number representation of a motion (or screw) has four parts; 1) magnitude, 2) dual pitch, 3) direction vector and 4) coupled vector. The magnitude and dual pitch capture the required range and the types of the motions respectively. The direction vector and the coupled vector is a line represented in dual vector form, thus it contains the orientation and location of the motion axis.

$$\begin{aligned}\hat{\$} &= M\hat{P}\hat{\mathbf{L}} \\ &= \left[M_{\max}, M_{current}, M_{\min}\right]\left(P_A + \varepsilon P_L\right)\left\{\mathbf{D} + \varepsilon\mathbf{C}\right\}\end{aligned} \tag{1}$$

Where M_{max}, $M_{current}$, and M_{min} represent the maximum, current and minimum value of the magnitude respectively. P_A and P_L represent the angular and linear pitches respectively. And **D** and **C** represents the direction and couple vector of the lines.

The range of motion is calculated as the $M_{max} - M_{min}$. If the magnitude is a single number then the motion is considered as the displacement from 0 to the magnitude. The dual pitch has two numbers; P_A and P_L. For a pure rotational motion and a pure translational motion, the dual pitches are $(1 + \varepsilon\ 0)$ and $(0 + \varepsilon\ 1)$ respectively. For a generic screw motion, the dual pitch is $(1 + \varepsilon\ h)$ and the unit of the magnitude is angle. The direction vector (**D**) indicates the direction of the motion axis. The couple vector is the cross product of the location of the line and the direction vector (**C** = **R** X **D**). Therefore, the dual vector satisfies the following conditions.

$$\begin{aligned}\left|\mathbf{D}\right| &= 1 \\ \mathbf{D}\cdot\mathbf{C} &= 0\end{aligned} \tag{2}$$

For the multi-DoF motions, the dual vector itself contains variables that capture the DoF. However, it is not desirable to have more than one DoF for a motion. Therefore, we will use multi-DoF dual vectors only for the intermediate motions and they will be decomposed into single DoF in the end.

The decomposition of the motion is required to match the required motions to the kinematic structure of the constraining leg. The decomposed motions can be directly used to synthesize the constraining leg since the order of screws also determines the dependency between the motions as in a serial kinematic chain.

The second step toward the design of CPKM is to configure the constraining leg for the required motions.

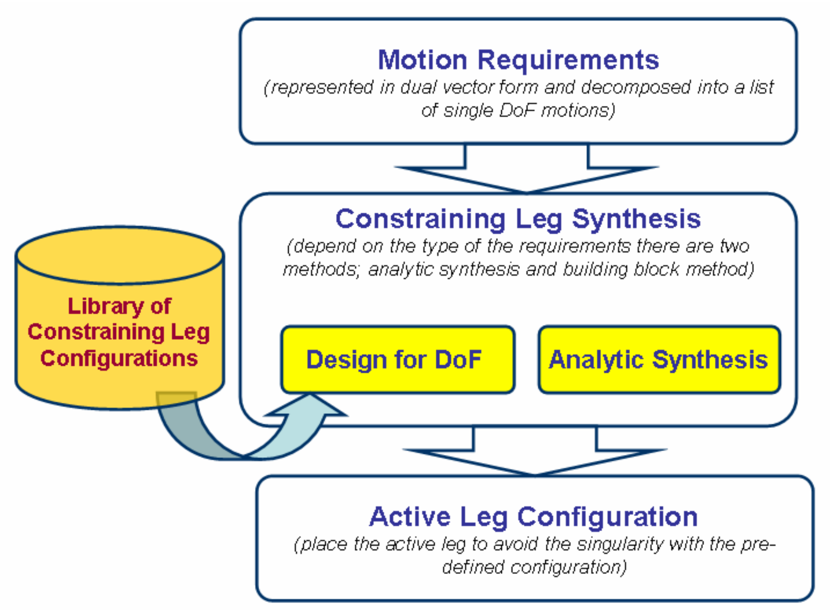


Figure 6. CPKM Design process

After configuring the constraining leg, the active legs should be added to complete the CPKM design. The generic design of the active legs is designed so that it has six DoF. However, the actual DoF of the active leg is five since the actuator constraints one DoF from the configuration. Now the active legs have five DoF, in other words each of them constraints one DoF, the active legs control the DoF of the CPKM with those constrained DoF and hence causes the singularity. In adding active legs, the arrangement should be carefully done otherwise it will cause redundancy or singularity.

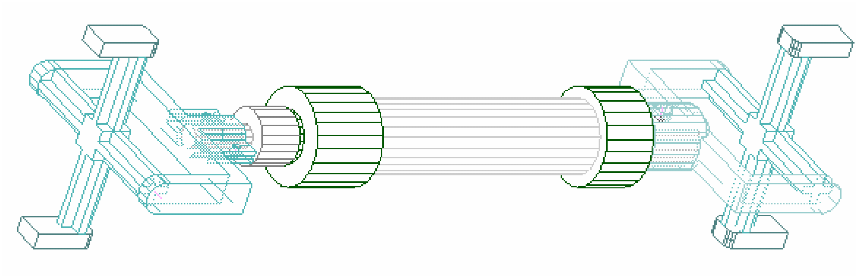
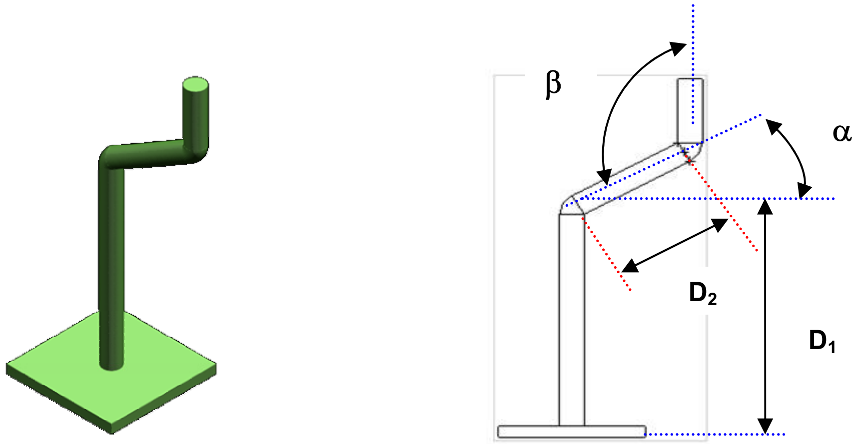


Figure 7. active leg design

4. Illustrative Part Family (PF) Definition and MDLD Process Planning

According to Shah and Mantyla [13] a solid model in which the main model entities, such as faces, edges etc., are related by geometric constraints defines a parametric solid model. The geometric constraints specify mathematical relationships between the numerical variables of the model entities. For the purposes of this research we shall define a part family to be the set of parametric solid models which share the same topology and geometric constraints. A member of the part family is instanced by assigning a value to each of the geometric constraints. We do not concern ourselves with constraint satisfaction or constraint propagation as addressed in [13] and [14]. Instead, our objective is to show the relationship between MDLD process planning and CPKM synthesis in the context of geometrically varying solid models.

An illustrative part family is shown in the following figure (ref. Figure 4).



(a) An instance of the Illustrative part family

(b) Geometric Constraints

Figure 4: Illustrative Part Family

In Figure 4, the geometry of the part varies as the parameters, α, β, D_1 and D_2 are changed. The following constraints are placed on the part family parameters:

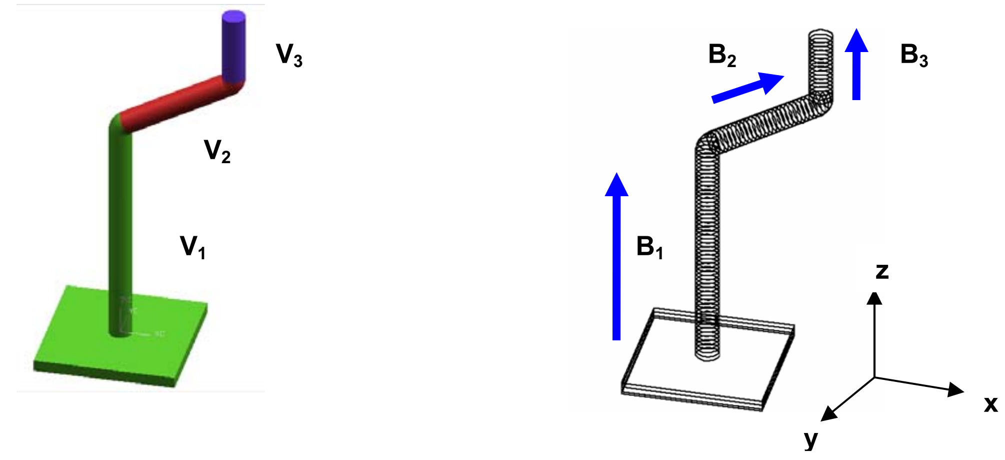
Parameter	Minimum Value	Maximum Value
α	-30^{o}	30^{o}
β	90^{o}	180^{o}
D_1	50 mm	150 mm
D_2	20 mm	60 mm

The diameter of the tubular section is fixed at 10 mm and the base dimensions are 50x50 mm.

In the following sections, we will present the MDLD process planning for the part families. The output from the process planning will be used to design a customized CPKM mechanism.

4.1. MDLD Process Planning for PF

MDLD process planning tasks for the part family are derived from those discussed in Section 2.0. The build directions for the part family vary with the geometric constraints which effects the resultant part volume decomposition. The process planning tasks for an illustrative part family member are shown in Figure 5. These include part volume decomposition and slicing. Uniform slice thickness is assumed throughout. Note that the sequence of deposition is $V_1 - V_2 - V_3$, based on the existence of the base surface (as discussed in Section 2.0). The deposition nozzle is assumed to be oriented along the build direction.



(a) MDLD decomposition **(b) Multi-Directional Slicing**

Figure 5: MDLD Process Planning for an illustrative PF member

B_1 ,(refer Figure 5b) the initial build direction is along the Z axis. The following table summarizes the variation in the build directions, B_2 and B_3 with the variation in α and β.

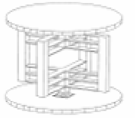
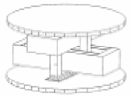
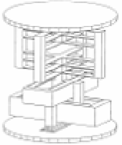
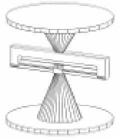
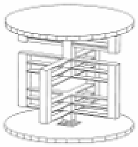
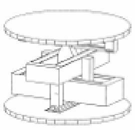
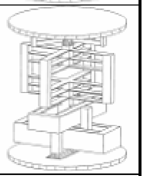
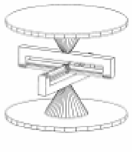
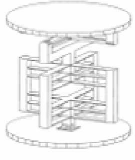
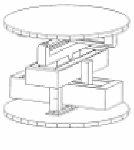
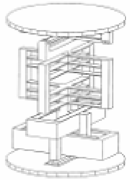
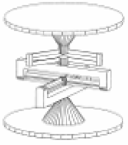
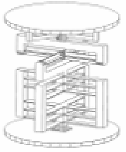
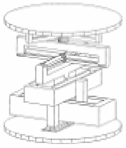
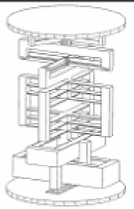
Build Direction	Dependence (x, y, z)
B_1	$(\cos\alpha, 0, \sin\alpha)$
B_2	$(-\cos(\beta - \alpha), 0, \sin(\beta - \alpha))$

5. Compliant Mechanism for fabricating the PF

The example has two build directions, B_1 and B_2. The task of the workpiece orientation unit is to orient the workpiece from the up-right to the oriented angle of B_2.

Therefore one can assume that the mechanism requires one degree of freedom which is: rotation about the Z axis in the global coordinates.

Table 1. Library of constraining legs for DoF requirements

Translation Rotation	0	1	2	3
0				
1				
2				
3				

From Table 1, the one rotation and no translation configuration is selected as the candidate configuration of the constraining leg. Since the mechanism need to orient the workpiece by angle α, the sizing of the compliant joint is determined to satisfy the motion range requirement [9].

After having the constraining leg configured, the active leg is placed. Since the mechanism needs only one degree of freedom, it needs one active leg. To balance the active leg layout, we put two active legs as in the figure 6.

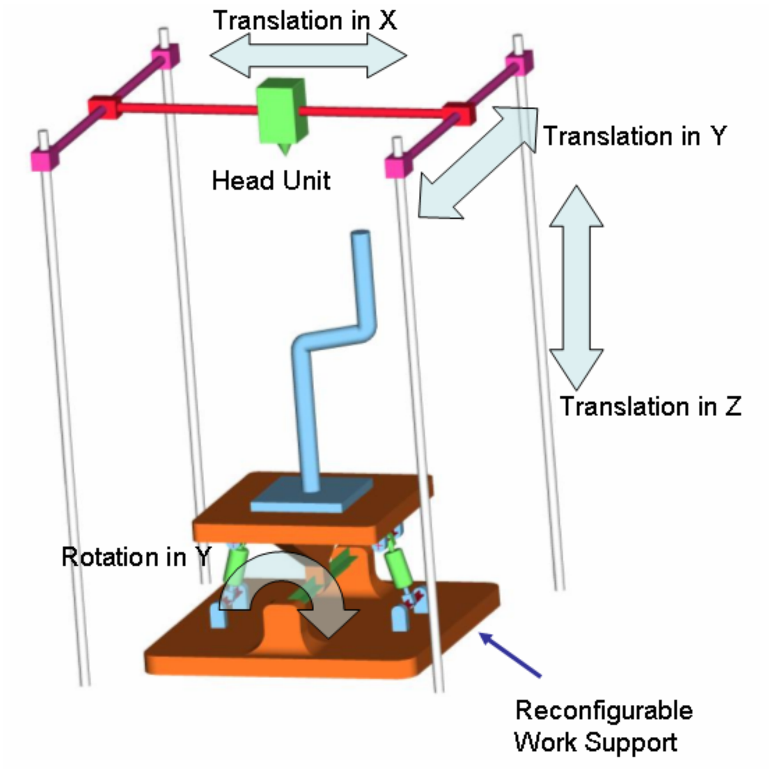


Figure 6: MDLD machine for PF member

As the part family changes, the reconfigurable work support unit could be replaced for the new requirements.

6. Conclusions and Future Work

In this research we have presented a synergistic framework in which the kinematics of an LM machine are designed using the output from the MDLD process planning for a parametric part family. The presented approach has the potential to be more cost effective when compared to MDLD systems which employ 5-6 axis kinematics. Our assumptions regarding the mode of material deposition are generic. Future research will be directed at interfacing with a specific deposition technique (such as Direct Metal Deposition (DMD) [7]). We will also focus on complex application specific part families. This will entail the inclusion of collision detection techniques resulting in the possible requirement for support structures and changes in the orientation of the deposition nozzle orientation.

References

[1] Alexander, P. and Dutta, D., “Part Orientation and Build Cost Determination for Layered Manufacturing”, Computer-Aided Design, 30, 1998, pp 343-358.

[2] Allen, S. and Dutta, D., "Wall Thickness Control in Layered Manufacturing for Surfaces with Closed Slices", Computational Geometry: Theory and Applications, Vol. 10, 1998, pp 223-238.

[3] Arcella, F., Albott, D., House, M., "Rapid Laser Forming of Titanium Structures", http://www.aerometcorp.com/rapid_laser_paper.htm.

[4] Dickens, P. et al., "Rapid Prototyping using 3D Welding", Solid Freeform Fabrication Symposium, 1992.

[5] Griffith, M. et al., "Laser Engineered Net Shaping (LENS) for Fabrication of Metallic Components", ASME International Mechanical Engineering Congress and Exposition, 1996.

[6] Hoschek, J. and Lasser, D., Computer-Aided Geometric Design, A.K. Peters, 1993.

[7] Mazumder, J., Choi, J., Nagarathnam, K., Koch, J. and Hetzner, D., "Direct Deposition of H13 Tool Steel for 3-D Components", JOM, 49, No. 5, pp. 55-60.

[8] McMains, S., "Double Sided Layered Manufacturing", Japan-USA Symposium on Flexible Automation, , Hiroshima, Japan , July 2002, pp.269-272.

[9] Moon, Y. and Kota, S., "Design of Compliant Parallel Kinematic Machines", AMSE DETC, Montreal, Canada, 2002.

[10] Moon, Y. and Kota, S., "Automated Synthesis of Mechanisms using Dual-Vector Algebra", Mechanism and Machine Theory, 37, 2002, pp 143-166.

[11] Singh, P. and Dutta, D., "Multi-Direction Slicing for Layered Manufacturing", Journal of Computing and Information Science in Engineering, June 2001.

[12] Singh, P. and Dutta, D., "Offset Slices for Layered Manufacturing", ASME DETC, Montreal, Canada, September, 2002.

[13] Shah, J. and Mantyla, M., Parametric and Feature-Based CAD/CAM, John Wiley and Sons, Inc., 1995.

[14] Shapiro, V. and Vossler, D., "What is a Parametric Family of Solid?", Third ACM/IEEE Symposium on Solid Modeling and Applications, Salt Lake City, 1995.

[15] Yang, Y., Fuh, J., Loh, H. and Wong, Y., "Multi-orientation Deposition for Support-less Layered Manufacturing Process", preprint.