The research is about developing a computerized design system for microtechnology-based energy, and chemical systems (MECS). MECS devices are a part of microfabrication, which primarily focuses on taking advantage of the extremely high rates of heat and mass transfer available in microstructures. It typically consists of intricate arrays of components interconnected within a single block of metal, ceramic, or polymeric material. In terms of size, MECS devices are in-between micro-scale and macro-scale fabrication, sometimes called meso-scale manufacturing.

The MECS devices are built by using the microlamination process. In contrast to conventional manufacturing, microlamination process builds the
product layer by layer, and joins those layers into a device by a bonding process. The final shape of a MECS device will dictate how each layer should be patterned and how it will be assembled together. Slicing the model into sufficiently thin layers convert the intricate array of components from the 3-D model representation into 2-D model.

Currently, there is no CAD system that provides a design tool that sufficiently accommodates the needs of the microlamination process. Instead of creating a brand new CAD system, the solution is to adapt an existing system to become an enhanced design tool for the microlamination.

The computerized design system for the MECS environment starts with designing the MECS device in a 3-D CAD solid model. This design information is then extracted and decomposed into features information. Using the features information, the layering process is accomplished by applying the orientation algorithm to determine the best orientation for the device. The slicing algorithm slices the device into layers according to the predetermined orientation. Within the software environment, this design and layering process is completed by implementing geometric modeling principles and utilizing computational algorithm.

The system is implemented in the SolidWorks CAD/CAM environment. Example parts and real MECS devices are presented to demonstrate the major step and verify the feasibility of the system developed. The system is capable to
orienting and slicing the devices that have all through type features, all non-through type features, or a combination of through and non-through type features.
Automated Feature Extraction For Orientation And Slicing
In Microlamination

by
Retna Ariastuti

A DISSERTATION
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the requirements for the
degree of

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Retna Ariastuti, Author
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Chapter 1 Introduction

The growth of manufacturing process technology in the last decade has made it possible to develop a product on the order of micrometer size. Many of these technologies use different approaches to solve manufacturing problems, when compared to conventional or macroscale manufacturing. In conventional manufacturing, individual components are cast, molded, stamped, milled, turned, and then assembled into systems and products. In contrast, the micro- and meso-scale manufacturing processes create devices and systems based on a different paradigm. In these paradigms, thin layers of metal, polymeric, and ceramic materials are sequentially laminated (deposited and shaped) using techniques such as chemical deposition, lithography, masking, bonding, and etching. Oxidation, doping, and heat treatment may further modify the material properties of individual layers. The key difference from conventional manufacturing is that the shaping and assembly operations may occur simultaneously and incrementally.

One of these new technologies is microtechnology-based energy, and chemical systems (MECS). MECS devices are a part of microfabrication, which primarily focuses on taking advantage of the extremely high rates of heat and mass transfer available in microstructures. This radically reduces the size of a wide range of energy, chemical and biological systems. In terms of size, MECS devices are in-between micro-scale and macro-scale fabrication, sometimes called meso-scale manufacturing.
The MECS environment uses the principles of a machining process to shape and assemble devices, called microlamination. This allows for the fabrication of micro and meso-scale systems having intricate arrays of components interconnected within a single block of metal, ceramic, or polymeric material. The material used in a MECS device must have the required mechanical and thermal properties for the functioning of the final device. The process begins by machining a shim of a base material (called a lamina) to the desired pattern shape. After patterning, each lamina is surface treated, stacked into a prearranged order, and then assembled to form a single block device. The assembly process selected for the MECS devices is the bonding process.

A bottleneck frequently encountered in conventional manufacturing is part fixturing. This is not a big problem in microlamination, since each layer is of the same size, and thus one support structure can be made for the whole product. Therefore, planning and manufacturing of complex and expensive fixturing devices is largely eliminated.

In conventional design, the translation of a functional specification into a physical object is not always easy to obtain and sometimes requires years of experience. Also, bringing manufacturing constraints upstream in the early design stages proves to be more difficult than anticipated by the design community, especially expressing manufacturing knowledge in the form of simple design rules.
This situation is also made more complicated by the increased of the geometry complexity of the part.

Layered manufacturing (LM) technology, which is much used in a rapid prototyping process, introduces a class of manufacturing methods that fabricate an object, layer by layer, from a CAD model. A distinct advantage of creating a part layer by layer is that the geometry complexity of the part has significantly less impact on the fabrication process than in the case of traditional, subtractive manufacturing processes.

The LM technology has some similarities to the microlamination process. Both create the final product layer by layer to construct a desired contour shape, but the shape being considered in LM technology is mostly an outer contour or an external feature, while in microlamination it is an inside contour or an internal feature.

The final shape of a MECS device will dictate how each layer should be patterned and how it will be assembled together. Slicing the model into sufficiently thin layers will convert the intricate array of components from the 3-D model representation into 2-D model. This will make production-process planning a lot easier than conventional manufacturing, because working with flat geometry will pose no additional complexity in the process.
1.1 Research Contribution

The development of a product traditionally consists of a series of design and manufacturing processes. The design processes include product design, detailed design, and design analysis. During its process, a design often needs to be modified through several iterations of prototype making and redesign, before it can be released for manufacturing. These iterations are called design improvements.

The manufacturing processes include production planning, machining, inspection, and assembly. Between the design and manufacturing process, there are process planning activities, which link design and manufacturing that includes process selection and resource selection. A typical process of design and manufacturing activities within any type of manufacturing system is shown in Figure 1-1.

![Figure 1-1. A production flow of a manufacturing system](image)

The microlamination process utilizes different methods of fabrication and manufacturing. Instead of using the final part design, it uses the layer design that
will build the final part. Each layer is designed separately and has its own planning and manufacturing processes. This is shown in Figure 1-2.

Figure 1-2. The microlamination design process

The drawback of using the individual layer design is that it is difficult to maintain the relationship between layers as the detailed design in one layer is closely related to the other layer. It is also difficult to verify the integrity of the final part design when designing it layer by layer.

This research proposes the utilization of the final part design instead of layers design as an input for the manufacturing process. Before entering the process planning activities, this final part is divided into layers by applying feature extraction, orientation and slicing algorithm. This activity will be called pre-process planning. The resulting layers composition is then sent to the process planning and manufacturing process and be built into a whole device. The proposed method is highlighted in the diagram of microlamination design process and is shown in Figure 1-3.
1.2 Research Goal

In order to develop a complete process planning system for microlamination, the pre-process planning activities have to be explored first, which will be the focus in this research. The research goal then is to develop an automated design system for pre-process planning in microlamination, which helps improve the design and planning of MECS device.

The system utilizes a 3-D CAD solid model of the device and evaluates all the features contained in it to establish the proposed layer compositions to build the device. The system is developed by taking advantage of the similarities between layered manufacturing and microlamination.

1.3 Research Strategy

The basic assumption from a design perspective is that the engineer has extensive freedom during the design process so that he/she can generate any kind of product design geometry that fulfills the product’s functional requirements. The
role of the downstream application, then, will be in verifying the design for its manufacturability.

In order to develop a computerized system for the MECS environment, the input of the system is the design geometry information for the product, which must be in CAD format for it to be automated. The first step to integrate design and manufacturing within the MECS environment (in this case the microlamination process) is to conduct a top-down design analysis to determine the layering scheme for the product. The layering scheme will dictate how the features are arranged in each layer. Since the thickness of each layer can be negligible during this stage, the feature definition can be limited to through-type features. This will allow the feature recognition algorithm to deal only with 2-D features, instead of complex 3-D features.

Currently, there is no CAD system that provides a design tool that sufficiently accommodates the needs of micro- and meso-scale manufacturing. Instead of creating a brand new CAD system, the proposed solution is to adapt an existing system to become an enhanced design tool for this new type of manufacturing. The basic modification is based on the fact that conventional manufacturing mainly employs a bottom-up approach in their design and production process, which is not so fit for the MECS paradigm of manufacturing.

When working with layers in two dimensions, as in micro and mesoscale manufacturing, it is possible to adopt a top-down design process. The approach
begins with the exploration and development of the functional requirements necessary to build the product, which are further converted into components and/or subcomponents. This initial design is developed using a 3-D CAD environment to achieve a cohesive understanding and clarity of the product being developed. The layering process is then accomplished by decomposing this 3-D model into thin cross-sectional slices. The final product is assembled by layering each layer on top of the previous layer, according to a predefined arrangement. Within the software environment, this design and layering process is accomplished by implementing geometric modeling principles and utilizing computational intelligence methods.

1.4 Research Implementation

In order to implement the research strategy, the research is broken down into several steps: (1) model development, (2) model implementation, and (3) model validation. In model development, the features types within the 3-D part model are identified and based on this, the orientation and slicing algorithm is developed. In model implementation, the algorithms are transformed into an applicable implementation in the CAD/CAM environment, which in this research is a SolidWorks environment. The implementation is verified by using example parts. The last step is to validate the system by using the real MECS devices. Three MECS devices are used: (1) the heat pump microchannel plate, (2) the biodiesel microchannel plate, and (3) the biodialysis microchannel plate.
This research is arranged according to those steps. Following a review of the relevant literature, each of these steps and the developed algorithms are described. The research concludes with some examples and results, and with a discussion of the limitations of this research and a view of future research needs for this area of design tools.
Chapter 2 Literature Review

Many research have been done in the area of microlamination process and layered manufacturing technology. This chapter describes the research that are related to the current research.

The first section describes the MECS devices and the microlamination process used in developing those devices. The second section describes the layered manufacturing technology, which is further divided into the orientation model and the slicing model that have been developed so far. The third section, which also the last one, describes the comparison between the microlamination process and the layered manufacturing technology. This last section also acts as the starting point for the current research.

2.1 Microtechnology-based Energy and Chemical Systems (MECS)

Microtechnology-based Energy and Chemical Systems (MECS) devices are a part of microfabrication, which primarily focuses on taking advantage of the extremely high rates of heat and mass transfer available in microstructures. MECS devices have dimensions on the order of 1 to 10 cm, which places them into the meso-scale range (between macro-scale and micro-scale manufacturing). It includes embedded microstructures, such as arrays of parallel micro channels with dimensions on the order of 100 microns in width and several mm in height. The benefit associated with reducing the scale of these devices to increasingly smaller
size includes: (1) improved portability; (2) disposability; (3) enhanced efficiency; and (4) reduced waste volumes where small scale process are required.

MECS devices are typically fabricated in metals, ceramics, and polymers; and use a microlamination method instead of other microfabrication techniques (Drost, 1999). The fabrication of MECS devices that have a complex series of internal features requires construction using vertical fabrication methods to achieve high-aspect ratio features (which is difficult or impossible to achieve using other methods, such as LIGA, bulk, or surface micromachining). Also, these conventional microfabrication techniques lack the capability for economical mass production. Microlamination offers the potential for mass production of low cost, relatively low volume product. The devices are designed such that they can be assembled in a stacked geometry.

The material used for MECS devices has been varied, and silicon is not the favored base material. Silicon has a much higher thermal conductivity than is desired for energy-based applications and it is brittle, expensive, and not easily tailored to specific environmental conditions. The functionality of MECS requires that they have the thermal, chemical, and physical properties of more traditional engineering materials such as metals or ceramics.

Many researchers have developed MECS devices. Martin, et.al (1998) developed a microdialysis device and microfluidic motherboard using plastic components. The motherboard platform was designed to be tightly integrated and self-contained (i.e., all liquid flows are confined within machined microchannels),
reducing the need for tubing for fluid distribution and connectivity. The motherboard consisted of three fluid reservoirs connected to micropumps by microchannels. The fluids could either be pumped independently or mixed in microchannels prior to being directed to exterior analytical components via outlet ports. The microdialysis device was intended to separate electrolytic solution from low volume samples prior to mass spectrometer analysis. The device consisted of a dialysis membrane laminated between opposed serpentine microchannels, and containing the sample fluid and a buffer solution. The laminated metal sensor consisted of fluid reservoirs, micro-flow channels, micropumps, mixing channels, reaction channels, and detector circuitry.

Matson, et.al (1997) developed a microchannel chemical solvent separation unit, which consisted of a series of parallel flow and counterflow microchannels separated by micromachined membranes and assembled into single unit by a lamination process. Components for the device were fabricated by laser micromachining, photochemical machining, and photolithographic patterning. The membranes were fabricated from stainless steel using photochemical machining and from polyimide material by using two distinct laser micromachining processes.

Matson, et.al (1998) also developed a stainless steel microchannel microcombuster. The device consisted of three parts: a laminated reactor body, a laminated combuster, and a solid cover plate. The laminated components were produced using stacks of photochemically machined stainless steel shims. When
formed into solid leak-tight components using a diffusion bonding process, the laminated parts were designed to contain a complex series of internal gas-flow microchannels that could not be produced in a solid metal block by any other fabrication method.

Martin, et.al (2000) developed laminated ceramic components for use in microfluidic chemical processing and energy management systems, including microreactors and biological reactors. Thin layers of green ceramic tape were patterned with microfluidic flow features fabricated by a number of cutting processes. The patterned layers were then stacked, and laminated with other layers of green tape, ceramic plate, or other materials using a series of processing steps. The resulting monolithic, leak-tight microfluidic ceramic components were capable of tolerating high temperature and/or chemically corrosively environments. As with other laminated metal and plastic microcomponents, channel aspect ratios could be very high, providing large surface area channels.

Paul and Terhaar (2000) developed two passive, one-way microvalves for microlamination architecture. The first is micro-flapper valve, which consisted of two 25mm x 25mm x 0.25mm laminae, a valve seat, and a hinged flap bonded together. One laminae contained the valve seat, which had an orifice opening of 1.5 mm, and the other contained the flapper mechanism, which consisted of a 3 mm hole with a 2.2 mm disk on the interior, held in place with a hinge that was approximately 300 microns across. The second device was a micro-float valve, which had a free floating disk that would seal against the valve seat when pressure
was applied in one direction, and float up to a ring nozzle that would permit fluid flow when the pressure was applied in reverse direction. The micro-float valve consisted of five laminae: (a) valve seat; (b) cylinder 1; (c) valve float; (d) cylinder 2; and (e) ring nozzle. The valve float contained the float mechanism, which had 80-micron wide fixture bridges. These bridges held the valve disk in place during bonding.

2.2 Microlamination

Lamination is a process commonly used to fabricate components that cannot be readily fabricated by conventional manufacturing techniques such as machining, casting, and molding. Complex shapes, internal cavities, flow chambers, and interconnects can be achieved by lamination techniques. The lamination process can also combine dissimilar materials to optimize the functionality of each level, chamber, or layer. The lamination process employed by MECS fabrication is further referred as the microlamination process due to the smaller scale of the devices.

The microlamination process steps include: (1) laminae patterning, (2) laminae registration, and (3) laminae bonding. The process begins by surface machining or through cutting of a single lamina with a pattern containing the desired structure. Once the pattern is cut, each of the laminae are surface treated, and stacked in prearranged order. The stack is then bonded together, forming a
single block of material. In preparing individual laminae, numerically controlled laser micromachining is used.

The lamination process requires the use of thin patterned shims that, when assembled in the appropriate arrangement, produce a series of thin gaps or voids which can act as flow channels or fluid headers. For devices incorporating microchannel arrays, the shims containing flow channel cutouts are alternated with shims that do not have the cutout areas. The shims without cutouts then act as fins between the channels. Channel widths are determined by the thickness of the material used to produce the channel shims. Channel heights and lengths are determined by the cutout area of the shims, and the channel aspect ratio (height/width) can be made as large as the material of the shim permits. Headers at the ends of the microchannels are formed by openings common to all the shims, and that are aligned when the shims are assembled prior to bonding. To increase the channel width beyond the thickness of the shims, two channel shims were included between each pair of fin shims. This type of patterned shim assembly method allows the fabrication of fluidic devices with internal structures not attainable by any other method (Martin, et al, 2000).

Use of the lamination assembly method allows flexibility in the design of the microchannels within the device. By simply replacing the channel layers with similar parts and different shim thicknesses, the channels widths in the finished part can be adjusted. Alternatively, by modifying the inlet and outlet header
arrangement, and replacing the fin layers with micro-machined membranes, a simple solvent/solvent extractor can be fabricated.

There are two microlamination approaches. One involves the production of functional components, formed by horizontally stacking multiple functional layers. The other involves the used of machined shims that are stacked vertically and then laminated to form solid devices containing complex arrays of internal microchannels. Both approaches are applicable to metal, polymeric, and ceramic laminates.

2.3 Layered Manufacturing

Layered manufacturing (LM) technology refers to a class of manufacturing methods that fabricate an object, layer by layer, from a CAD model. A distinct advantage of creating a part layer by layer is that the geometry complexity of the part has significantly less impact on the fabrication process than in the case of a traditional, subtractive manufacturing process. Currently, LM technology has moved beyond prototyping, and now includes complex functional parts. Therefore, from the designer's perspective, LM removes traditional manufacturing constraints and expands the design space (Kulkarni and Dutta, 1996).

Since LM is a fundamentally different method of manufacture, with unique informational needs, there are new issues in the design, representation, and modeling of parts and the data, transferred between design, process planning and manufacturing module (Kulkarni, et al, 2000). As in traditional manufacturing,
process planning involves determining the machining process sequence and parameters to convert a workpiece from the initial form, and into the final form from an engineering drawing. In LM, the engineering drawing is replaced by a CAD model and the machining process by an LM process. There are three tasks that are typically needed to enable automatic and efficient fabrication of LM: (1) orientation determination; (2) support structure generation; and (3) slicing and path planning. The result of a preceding step acts as an input to the following step.

A different approach for generating fabrication sequences for surface micromachined structures was developed by Gogoi, et al (1994). Their method automatically generated the fabrication sequences from a two dimensional geometrical description. This method translated the device geometry into layers and a mathematical representation of layer order. All possible process sequences were extracted from the layer order in terms of fundamental processing steps like deposition, lithography, and etching using topological sorting techniques. In general, the fabrication sequence is not unique. Hence, an optimal sequence was selected from the set using a cost function based upon a database of materials and process. A synthesis program that implemented the sequencing algorithm and optimization was developed and the output was a complete optimal fabrication sequence in human-readable form.

2.3.1 Orientation Determination

The orientation problem is to determine a transformation matrix, such that after applying the transformation to the object, the build direction aligns along the
vertical axis (z). Different factors that can be considered while choosing the build direction or orientation for LM are (Kulkarni, et al 2000): (a) maximizing the number of perpendicular surfaces; (b) maximizing the number of upward facing (horizontal) surfaces; (c) maximizing the number of holes with axes aligned in the slicing directions; (d) maximizing the number of curved cross-sections lying in the horizontal plane; (e) maximizing the area of the base surface; (f) minimizing the number of sloped surfaces; (g) minimizing the total area of overhang surfaces; (h) minimizing the number of trapped volumes.

There are many different approaches to solving the orientation problem. Frank and Fadel (1995) developed a methodology to find optimal orientation using a rule-based expert system. Taking into consideration surface finish, building time and the need for a support structure, a set of rules was developed in order to find the optimal orientation. If an optimal orientation was not possible, the tool helps the user to select an acceptable build direction. By introducing an expert system and allowing users to define their own specific rules in the system, the method incorporates human intelligence into the orientation selection process.

Cheng, et al (1995) developed multiobjective optimization of part building orientation in stereolithography. The primary objective was to find the variance of accuracy between different orientations based on types of surface. The secondary objective was to determine the optimal orientation if there were multiple orientations found from the primary objective.
McClurkin and Rosen (1998) developed an automatic and computer-aided build style decision support system for orientation determination. The quality of the final part can be controlled by changing one of several build style variables, including orientation or cross sectional layer thickness according to the user’s preference. The final process plan is determined by employing a response surface methodology and multi-objective decision support to select the orientation while considering many goals such as user’s preferences, accuracy, and the speed of build for the manufactured part.

Other approach to solving the orientation problem is by using optimization technique. Xu, et al (1997) developed an optimal orientation with number of slices as criteria to find the minimum layer thickness allowed to build a certain part. It takes into account building time, accuracy, and part stability to determine the optimal orientation. Its entire procedure from orientation to slicing process has been implemented in a CAD system.

Yang and Chen (2000) and Yang, et al (2001) developed the build orientation criteria based on feature accessibility during machining and number of support required to build a part. They developed the algorithm for robot-based layered manufacturing. Hence, the accessibility is based on the ability of the tool to approach certain points on the model surface because of the existence of local interference and global interference.

Choi and Samavedam (2002) determined an optimal orientation for the minimum build-time. The algorithm first rotates the part such that its height is at
the possible minimum height, and the vertical axis is fixed at the z-axis along the build-direction. Then, the algorithm rotates the parts about the x- and/or y-axis within a given range at a specific interval to determine the surface accuracy. For each orientation, the algorithm determines the cusp factor. If the maximum cusp height exceeds the given value, that orientation is not considered. The orientation that gives the minimum average value of cusp height is the preferred orientation of the part because it will achieve good surface accuracy.

2.3.2 Slicing

The slicing problem is to determine the thickness of individual layers for layered manufacture of the entire part. The task of slicing involves intersecting an oriented CAD model with horizontal slicing planes. Slicing can either be uniform, where the intersecting planes are a constant distance apart, or adaptive, where the distance between successive planes varies depending on the surface curvature of the model. The layer thickness, however, cannot be less than the minimum thickness achievable within the manufacturing process.

In current practice, a 3-D CAD model is usually triangulated into an intermediate form, the STL (Stereolithography Tessellation Language) file, which has become the facto standard in the industry (Lee and Choi, 2000). The STL file has advantages due to its simple structure, which contains only triangles and their normal vectors.

Research on the slicing problem generally can be divided into three main types: (1) uniform slicing; (2) adaptive slicing; and (3) direct slicing.
2.3.2.1 Uniform Slicing

Many layered manufacturing machines currently use a uniform slicing method that keeps the thickness of all layers constant. It simplifies the calculations involved in generating slices. The boundary of the part is a stepped approximation of the boundary of the original CAD model after uniform slicing. However, this method neglects the geometry of the object, and hence results in a less accurate part.

Choi and Samavedam (2002) used this uniform slicing method in their rapid prototyping process in order to build the virtual reality for virtual rapid prototyping model.

2.3.2.2 Adaptive Slicing

Adaptive slicing is a scheme that uses variable layer thickness based on the geometry change of the model along the build direction. This method uses a smaller thickness layer where the slope is flatter and a large thickness for a steeper slope. This method is also faster compared to the uniform slicing method since it may require fewer slices for a given height.

Lee and Choi (2000) generated optimal slice data by sampling point rapidly at the contour lines instead of at arbitrary point on the surface. Their method reduced the staircase error as it resulted in the minimum layer thickness and gave faster execution time.

Zhou, et al (2004) developed an adaptive slicing by considering the local geometrical information on the build direction and quality requirements for
various part surfaces. These quality requirements included the staircase effect and material tolerance.

Zhang and Liou (2004) used an adaptive slicing for a multi-axis LM. In the five-axis slicing process, the cutting planes are not parallel to each other as in the single axis LM. The slicing direction was generated based on the outer boundary of slices. The internal loops that were created from the cavities and depression features were not taken into account. These features were dealt with separately and processed by integration of the machining process.

2.3.2.3 Direct Slicing

The drawback of using the STL format is that the topology information of the drawing is lost since it approximates the model surfaces using an unordered set of triangular patches. And, for a 3-D model having freeform surfaces, the size of the STL file increases drastically owing to small triangular patches. This encourages the development of direct slicing. The direct slicing generates slicing data directly from the original CAD files without an intermediate STL format. It is preferred because it helps keep the geometric and topological robustness that the original data have and no intermediate conversion process is required.

This CAD files in the format of STEP file for slicing method have been used by Broek, et al (2002), Zhou, et al (2004), and Starly, et al (2005). Kulkarni and Dutta (1996) utilized the CAD model to obtain the surface information in the form of its parametric representation and used them to find the accurate slicing layer.
2.3.2.4 Feature-based Slicing

The different approach to solve the slicing problem is by using a feature-based method. A feature is defined by Shah and Mantyla (1995) as a representation of the engineering meaning or significance of the geometry of a part or assembly.

Yang, et al (2003) developed a feature extraction technique to be applied in the LM. The aim is to improve the LM process efficiency by considering the specific feature information of the model, which has been neglected in the previous research. The features are extracted from a geometric analysis in the LM domain, and by using a volume decomposition technique; each feature is analyzed separately by a process planner module. As in the feature definition used in the traditional manufacturing domain, features of interest must be related to the specific manufacturing process. In the LM process, each feature is defined based on the method used to fabricate it.

Qian and Dutta (2001) also used a volume decomposition technique to extract the features from the model. Each feature is sliced separately and independently and then further combined or merged together using additional algorithm to build a whole part. Their research also discussed how features interact with each other in the LM domain.

Ilinkin, et al (2002) developed a decomposition approach to LM process. The model was decomposed by a plane, which act as a slicing layer, into several pieces that can be built independently and then glued together. They devised
geometric algorithms to decompose both convex and non-convex models so as to minimize the contact area and the volume of supports. The normal of the decomposition direction will be the slicing plane or layer.

Lee, et al. (2002) developed surface reconstruction technique for slicing process. It was used in variable lamination manufacturing (VLM). The objective is to reconstruct the surface of the original 3-D CAD model in order to generate mid-slice data to generate tool path data, reduce building time, and improve the surface finish of the part. This VLM is able to generate 3-D layers instead of 2-D layers as it is in the regular rapid prototyping.

2.4 Microlamination and Layer Manufacturing

Microlamination and layered manufacturing have some similarities in how they build a part. Both decompose the part into layers and build the part by stacking up those layers together using certain method. Microlamination uses more complex process than LM to build the part, which is bonding process. The bonding process takes into account the material and its properties used for each layer. It also needs tooling, fixturing and other activities of conventional manufacturing during the bonding process. In LM, the unique feature is the direct fabrication, in which it does not need tooling and other peripheral activities to build the part (Dutta and Shpitalni, 2000). Therefore, it is possible to start from a CAD model and create the part in a very short time.
The output of each process is different. The LM technology is mainly used in rapid prototyping, while microlamination is used to build the final part. Microlamination put emphasis on the internal structure design or feature, while LM technology is on external feature or a combination of internal and external feature. This will make a difference in the design and planning process for both processes. Other comparison of microlamination and LM technology is described in Table 2-1.

**Table 2-1. Comparison of microlamination and LM technology**

<table>
<thead>
<tr>
<th></th>
<th>Microlamination</th>
<th>Layered Manufacturing</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input</strong></td>
<td>Engineering drawing</td>
<td>CAD model</td>
</tr>
<tr>
<td><strong>Feature Type</strong></td>
<td>2.5D internal feature</td>
<td>3D external</td>
</tr>
<tr>
<td><strong>Feature Extraction</strong></td>
<td>None</td>
<td>Volume</td>
</tr>
<tr>
<td><strong>Process</strong></td>
<td>Layer</td>
<td>Layer</td>
</tr>
<tr>
<td><strong>Planning Method</strong></td>
<td>Individual Layer</td>
<td>Orientation and slicing</td>
</tr>
<tr>
<td><strong>Output</strong></td>
<td>Part</td>
<td>Prototype</td>
</tr>
</tbody>
</table>

The LM technology has evolved for decades, and many research have been done to establish the design and planning process. By taking advantage of the similarities between microlamination and LM technology, the new approach to designing and planning in microlamination is developed.
Chapter 3 Model Development

Notational Index

- \( F_a \): set of all cylindrical faces
- \( F_p \): set of all planar faces
- \( V_i \): normal vector of face type \( i \)
- \( V_s \): current possible cutting vector
- \( V_s[n] \): set of \( n \) cutting vectors
- \( V_{a_i} \): axis vector of cylindrical faces
- \( V_{p_i} \): normal vector of planar faces
- \( F_n \): set of faces with its normal parallel to cutting vector \( n \)
- \( V_n\text{Cut} \): normal vector of the cutting planes found in a model part
- \( V_n C \): normal vector of planes along a cutting plane
- \( Z_c \): \( z \) value of the origin point of \( F_n \)
- \( Z\text{Array} \): set of \( Z_c \) value of \( F_n \)
- \( t \): the thickness of a layer

3.1 Introduction

The conceptualization of the lamination process may be divided into: (1) the Model Domain and (2) the Layer Domain. Model domain is also called pre-process planning activities. Activities attributed to the Model Domain are (a)
orientation and (b) slicing. These activities require geometric information from the 3-D model and the output data pertains to the whole model. In the Layer Domain, the activities are concerned with the generation of data for the manufacture of individual layers, which are the building blocks for the complete object. This decomposition is shown in Figure 3-1.

The tasks in the model domain are concerned with the efficient manufacture of the overall model. The tasks in the layer domain affect the manufacture of the exterior boundary and the interior of the individual layers. Some decisions in the model domain affect the outcomes in the layer domain. In general, the tasks in the model domain have to be completed before proceeding to the layer domain.

The orientation task in the model domain determines the feasibility of the subsequent slicing task. It evaluates the part and its features and decides whether it is possible to cut the parts into layers using the evaluation rules.

The slicing task in the model domain is to determine the thickness of individual layers that build up the entire part. The task of slicing involves
intersecting an oriented CAD model with horizontal slicing planes. Slicing can either be uniform, where the intersecting planes are a constant distance apart, or adaptive, where the distance between successive planes varies depending on the surface curvature of the model. The layer thickness, however, cannot be less than the minimum thickness achievable within the manufacturing process. The layer generated is a 2 1/2-D model, which is a normally-directed, linear extrusion of a two dimensional contour. Thus, the exterior of the layer is approximated by vertical walls, instead of a curved boundary.

3.2 Features in the Lamination Process

The features for a MECS device are mostly internal features. The features in the model domain are divided into features for orientation and features for slicing and they are 2-D features. A feature in the layer domain is mostly the same as a traditional manufacturing feature, and can be divided into 2-D and 3-D features.
3.3 Model Domain Development

The tasks in the model domain are the orientation and the slicing. Each task is described below.
3.3.1 Orientation Modeling

The fundamental problem in the model domain is the orientation problem. Orientation determination involves an analysis on the whole CAD model and it is done in the native format in which the CAD model was created.

3.3.1.1 Orientation Model Objective

In the microlamination, the orientation algorithm is used to find the best orientation for the slicing process according to the features contained in the part. The best orientation is selected to minimize the possible turbulence in the channel that might occur due to the presence of certain feature type and to prevent the lamination process (bonding process) is to be done in a costly manner.

The possible turbulence might occur when there is a staircase effect during the slicing process. This staircase is caused by slicing the cylindrical surface parallel to its axis. To avoid this, then, the part should be oriented in a way that all the cylindrical surfaces in the part are being cut along its axis.

The part also must be oriented in such a way that it always has the flat surface as a bottom reference. This will prevent the slicing process to be done in a way that it will be difficult for the part to be laminated (bonded).

3.3.1.2 Geometric Input

The part design is represented in a format that can be used further in subsequent processes; in this case the design resides in a 3-D CAD solid model.
From the many CAD model representations, the solid model was chosen because it contains the most complete information about the design, and there is no need to convert it into another format as the program directly uses this model in its operation.

The program reads the part's solid model and runs the orientation determination algorithm, which generates the possible orientations for the slicing process. The algorithm recognizes and categorizes all features included in the part, and for each feature found, it determines feature orientation relative to the other features using both/either the feature axis or the face normal of the feature.

3.3.1.3 Orientation Evaluation Rules

To determine the orientation, it is necessary to identify the surface type. Though somewhat analogous to the type of feature based surfaces used in a traditional manufacturing process, the types of surfaces in layer manufacturing are different because only form and directional information for each type of surface is required. The surface types are planar and cylindrical surfaces, and these surfaces are represented by the face normal (for planar surfaces), and by their axis of revolution (for cylindrical surfaces). In any layer building orientation, the part is defined with its base on the x-y plane and the building orientation along the z-axis.

The relations between feature directions can be divided into parallel, perpendicular, or non-parallel and non-perpendicular. Also, there is relation between a feature and its slicing direction. A planar face can be sliced in any of the
three normal directions, while the cylindrical surface can be sliced only in one
direction (along its axis) in order to avoid a staircase effect along the cylindrical
walls during the manufacturing process. Based on this, the relationships between
these surfaces are important in determining the final slicing direction for the whole
device.

Determining the relation between features is done by converting the face
normal and/or axis into a vector. Then, the scalar and cross products of the vectors
will categorize the features as parallel, perpendicular, or non-parallel and non-
perpendicular.

The basic principle of the orientation algorithm is that the first surface
found acts as a base feature for the remaining features, and it generates the first
candidate for the possible orientation direction or cutting vector of the part. The
axis or normal of the next surface found is compared to the first candidate: if the
face normal or axis is parallel to one or all of the current solutions, it will be
ignored because it will not contradict the current solution. If it does not pass the
criteria, the current solution will be updated and there will be a new candidate.

The result of the orientation determines the way the part will be sliced. If
the part is oriented along y-axis, the normal of the slicing layer will be parallel to
y-axis. This situation is depicted in Figure 3-4.
Figure 3-4. The prismatic part is sliced along the y orientation direction

If the part is oriented along x-axis, the normal of the slicing layer will be parallel to x-axis. This situation is depicted in Figure 3-5.

Figure 3-5. The prismatic part is sliced along the x orientation direction

If the part is oriented along z-axis, the normal of the slicing layer will be parallel to z-axis. This situation is depicted in Figure 3-6.
Figure 3-6. The prismatic part is sliced along the y orientation direction

If the part is oriented along the axis of a cylindrical surface, the normal of the slicing layer will be parallel to that axis. This situation is depicted in Figure 3-7.

Figure 3-7. The cylinder part is sliced along its axis
3.3.1.4 Brief Review of Relevant Vector Mathematics

Every feature in a part is represented either by its normal or its axis. These feature normal and features axis is then converted into vectors in order to determine the relationship between the features in a part. Two features are perpendicular or parallel to each other is determined by using their scalar product or cross product of their respective vectors.

The magnitude of a vector is

\[ |A| = \sqrt{A_x^2 + A_y^2 + A_z^2} \]  

(Eq.1)

where \( A_x, A_y, A_z \) are the Cartesian components of the vector \( A \).

The scalar (dot or inner) product of two vectors \( A \) and \( B \) is a scalar value given by

\[ A \cdot B = B \cdot A = A_x B_x + A_y B_y + A_z B_z = |A||B| \cos \theta \]  

(Eq.2)

where \( \theta \) is the angle between \( A \) and \( B \). Therefore, the angle \( \theta \) between two vectors is given by

\[ \cos \theta = \frac{A \cdot B}{|A||B|} \]  

(Eq.3)

The vector (cross) product of two vectors \( A \) and \( B \) is a vector perpendicular to the plane containing \( A \) and \( B \) and is given by
\[
A \times B = \begin{vmatrix}
\hat{i} & \hat{j} & \hat{k} \\
A_x & A_y & A_z \\
B_x & B_y & B_z
\end{vmatrix}
= (A_y B_z - A_z B_y) \hat{i} + (A_z B_x - A_x B_z) \hat{j} + (A_x B_y - A_y B_x) \hat{k}
\]
\[
= (A \parallel B \sin \theta) \hat{i}
\]
(Eq.4)

where \( \hat{i} \) is a unit vector in a direction perpendicular to the plane of \( A \) and \( B \).

Two vectors \( A \) and \( B \) are parallel if only if
\[
\hat{n}_A \cdot \hat{n}_B = 1 \text{ or } |\hat{n}_A \times \hat{n}_B| = 0
\]
(Eq.5)

where \( \hat{n} \) is the unit vector in the direction of the corresponding vector.

Two vectors \( A \) and \( B \) are perpendicular if only if
\[
\hat{n}_A \cdot \hat{n}_B = 0 \text{ or } |\hat{n}_A \times \hat{n}_B| = 1
\]
(Eq.6)

3.3.1.5 Orientation Problem Description and Algorithm

Objective: find all possible orientation directions for the slicing process of the part

Given: 3-D solid model

Algorithm:

1. Initialization:
   a. Get the information for the part from a solid model.
      i. The part will be represented by a total of \( n \) faces \( F_i \), where \( i = 0, \ldots, n \).
ii. Face type will be arc/cylindrical ($F_a$) or planar ($F_p$). In other words,

$$\forall i, F_i \leftrightarrow (F_i \in F_a) \cup (F_i \in F_p)$$

b. Assign an array of size 3 for cutting vector ($V_s [3]$). Cutting vector is a possible orientation direction. For a 3-D model, there will be three possible directions, aligning with $x$, $y$, or $z$-axis in the Cartesian coordinate.

2. Search through all the faces of part. In this step, the external faces will be ignored, because they are not used in determining orientation. The first internal face found will be evaluated to determine the current possible orientation or cutting vector candidate. There are two possible conditions at this point: Case 1 (cylindrical surfaces) and Case 2 (planar surfaces).

**Case 1.** For $F_i \in F_a$, find the axis of the surface ($V_{a_i}$)

If $V_s = \emptyset$, then $V_s [0] = V_{a_i}$.

In the case where the first feature is an arc or cylindrical surface; then the current possible orientation direction is the same as the direction of its axis. There is only one possible orientation ($n = 1$) for this type of surface; hence, the cutting vector is assigned to $V_s[0]$. 

If \( Vs \neq \emptyset \), then compare \( Va \) with \( Vs[j] \), \( j = 0, 1, 2 \).

If there is already a candidate of cutting vector, \( Vs[j] \), then the attributes of the next surface found have to be evaluated and compared to the current candidate. The candidate cutting vector will become the cutting vector if it is parallel to \( Va \). Otherwise, the cutting vector will be \( Va \).

If \( Va \parallel Vs[j] \), then \( Vs[0] = Va \) and \( n = 1 \);

If \( Va \perp Vs[j] \), then there is no possible cutting vector;

If \( \neg(Va \parallel Vs[j] \) or \( Va \perp Vs[j] \), then there is no possible cutting vector.

**Case 2.** For \( F_i \in F_p \), find the surface normal for the face \( (Vp_i) \).

Continue searching through the part faces. There are two possible conditions at this point:

If \( Vs = \emptyset \), then \( Vs[0] = [1,0,0] \), \( Vs[1] = [0,1,0] \), and \( Vs[2] = [0,0,1] \)

If this first feature is a planar surface, and because planar surfaces can be sliced in three directions without having to be concerned about the staircase effect, then the possible orientation directions are in the same direction as each of the three normal vectors of its surfaces, or in any direction of the three axis; \( x \), \( y \), and \( z \). Hence, the cutting vectors are assigned as \( Vs[0] \), \( Vs[1] \), and \( Vs[2] \).

These three current possible directions could be cancelled or kept by further searching through subsequent features. If the next feature is a cylindrical
surface, then the direction, which is not parallel to its axis, will be eliminated. If the next feature is a planar surface, then the three directions will be kept.

The algorithm is described as following:

For \( V_s \neq \emptyset \), there will be three possible situations: (a) there is already one candidate of cutting vector \((n=1)\); (b) there are already two candidate cutting vectors \((n=2)\); or (c) there are already three candidate cutting vectors \((n=3)\).

For \( n = 1 \)

\[ V_s[0] = V_p, \] there will be only one possible cutting vector.

For \( n = 2 \), then compare \( V_p \) with \( V_s[j] \), \( j = 0, 1 \).

If \( V_p \parallel V_s[j] \), then there will be two possible cutting solutions and these are the same as the current solution \( V_s[0] \) and \( V_s[1] \).

If \( V_p \perp V_s[j] \), then \( V_s[0] = V_p \), and \( V_s[1] = V_s[0] \times V_p \), and \( n = 2 \).

If \( \neg (V_p \perp V_s[j]) \), then \( V_s[0] = V_s[0] \times V_p \), and \( n = 1 \)

For \( n = 3 \), then compare \( V_p \) with \( V_s[j] \), \( j = 0, 1, 2 \).

If \( V_p \parallel V_s[j] \), then there will be three possible cutting solutions and these are the same as current solution \( V_s[0], V_s[1], \) and \( V_s[2] \).

If \( V_p \perp V_s[j] \), then \( V_s[0] = V_p \), and \( n = 1 \)

If \( \neg (V_p \perp V_s[j]) \), then there will be no solution.
When implemented, the algorithm does an exhaustive search of the part surfaces, and the result of this algorithm is information about the relationship between features to determine the orientation direction for slicing the part into layers. The relationships between features in a part are summarized in the following table (see Table 3-1). The arrow represents the direction of orientation in the Cartesian coordinate of the slicing process, where planar features are represented by cubes, and cylindrical features are represented by cylinders.
Table 3-1. Feature relationships in a part

<table>
<thead>
<tr>
<th>ComparisonFeat.</th>
<th>CurrentFeat.</th>
<th>z</th>
<th>y</th>
<th>x</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Cube" /></td>
<td><img src="image" alt="Cylinder" /></td>
<td><img src="image" alt="Cylinder" /></td>
<td><img src="image" alt="Cylinder" /></td>
<td><img src="image" alt="Cylinder" /></td>
</tr>
<tr>
<td><img src="image" alt="Uparrow" /> <img src="image" alt="Up" /></td>
<td><img src="image" alt="Up" /></td>
<td><img src="image" alt="Up" /></td>
<td><img src="image" alt="Up" /></td>
<td><img src="image" alt="Up" /></td>
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<tr>
<td><img src="image" alt="X" /></td>
<td><img src="image" alt="X" /></td>
<td><img src="image" alt="X" /></td>
<td><img src="image" alt="X" /></td>
<td><img src="image" alt="X" /></td>
</tr>
<tr>
<td><img src="image" alt="Up" /> <img src="image" alt="X" /></td>
<td><img src="image" alt="X" /></td>
<td><img src="image" alt="X" /></td>
<td><img src="image" alt="X" /></td>
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<td><img src="image" alt="X" /></td>
<td><img src="image" alt="X" /></td>
<td><img src="image" alt="X" /></td>
</tr>
</tbody>
</table>

Note: ![X](image) = no solution
3.3.2 Slicing Modeling

The slicing process is done on a CAD model, which already has had the orientation direction or cutting vector determined. The model is in a 3-D solid model with the cutting vector information is saved in the vectors array.

When the slicing algorithm is run, the program reads the part’s solid model and its cutting vector information. It generates the position of the cut for each cutting vector. Based on this position, the solid modeler builds the cutting planes, which separate the part into layers. The resulting layers, then, are saved into its own, individual format.

3.3.2.1 Slicing Model Objective

The slicing algorithm is developed to slice the part into layers; so as each layer will be composed of set of through-cut features. The layers with through-cut features will increase the accessibility to manufacture the features.

The algorithm will find all the features that will be cut through by each of the possible orientation, and it will slice it according to the smallest thickness (height) among those features.
3.3.2.2 Slicing Evaluation Rules

The evaluation process is applied to each cutting vector. The slicing layer (or cut) is determined by evaluating all features that are cut through by the cutting vector. These features are then decomposed into its faces, and only faces that have its normal parallel to the cutting vector that are being evaluated. Also being evaluated in this step is the features' dimension along the cutting vector. The features that have different dimensions along the cutting vector will be cut with the thickness based on the smallest dimension among those features. Thus, one feature could be cut into several layers, while other feature could be cut at a thickness of its own.

The process in which one feature is cut into several layers is shown in Figure 3-8. In this case, after evaluating the features in the part, there is at least one other feature in the part that has smaller height than the feature depicted in Figure 3-8. Hence, the feature will be sliced into layers with the slicing thickness is the same as the height of the lowest feature.
Figure 3-8. Slicing process with one feature is cut into several layers

The resulting layers for the feature are depicted in Figure 3-9.
The process in which one feature is cut into its own single layer is shown in Figure 3-10 and Figure 3-11. In this case the slicing thickness is the same as the height of the feature being considered. Figure 3-10 shows a part that has two
features, Feature 1 and Feature 2. With only these two features in the part, the layer thickness will be the same as the height of each feature.

Figure 3-10. Slicing process with features being cut into its own layer

The resulting layers for the part in Figure 3-10 are shown in Figure 3-11.
Figure 3-11. The result of the slicing process of features in Figure 3-10.

The resulting layers are then treated as an individual component of the part, and are stored separately for further processing.

### 3.3.2.3 Slicing Problem Description and Algorithm

**Objective:** slice the model into layers

**Given:** cutting vectors

**Algorithm:**

1. **Initialization.** For each possible orientation direction or cutting vector in $V_s[n]$, orient the part such that the cutting vector is always parallel to $z$-axis direction in the Cartesian coordinate system.
a. For each cutting vector of the part that has been oriented (VnCut), find Fn, that is, all faces/surfaces which have normal or axis that is parallel to the direction of cutting vector, and set the normal direction of Fn as VnC.

\[ \forall (VnCut), Fn \Leftrightarrow (Fn \in Fa) \cup (Fn \in Fp) \cup (VnC \parallel VnCut) \]

b. Find the origin point of Fn. Set the z value of the origin point of Fn as Zc and save it into ZArray. ZArray is an array that contains all z value for each Fn found.

2. The value for each Zc in ZArray will determine the position of slicing process. The difference between the Zc values in the ZArray will be the required thickness of each layer in the part. The thickness of a layer, t, will be:

\[ t = Zc_i - Zc_{i-1}, \text{ where } i = 1, \ldots, \text{ number of slicing positions} \]

a. The Zc values that are used for determining the layer thickness need to be sorted to avoid the misinterpretation of the slicing position. This is due to the fact that the process of finding the face/surfaces in the solid modeler is done in an unordered sequence. The slicing position along the cutting vector, Zc, before sorting process is done is depicted in Figure 3-12 and the slicing position after it is sorted is in Figure 3-13.
3. The final slicing positions and the layers thicknesses are recorded and sent back to the part solid model where the slicing process is performed.
Chapter 4 Implementations

The implementation program has been developed using C++ on a personal computer to test the feasibility of the algorithm. This program has been integrated into the SolidWorks CAD/CAM system so that example parts can be created and tested. Given the 3-D solid CAD model of the parts, the program analyzes the surface information of the parts, identifies the possible orientation directions for slicing, and finally slices the part into layers along this slicing orientation. The result is displayed in an exploded view and/or a drawing file.

The first program implemented was to analyze the surface and face information of the part and to determine its possible orientations. This program was divided into three parts: (1) the program for the parts having arc and cylindrical surfaces; (2) the program for the parts having planar surfaces; and (3) the program for the parts having both arc/cylindrical and planar surfaces.

The second program implemented was to utilize the possible slicing orientation directions found in the first program to slice the parts into layers. This program is comprised of three parts: (1) the program for finding the possible slice positions based on the features contained in the parts; (2) the program for determining the fixed position of each slice and the thickness of each layer; and (3)
the program for displaying the original part model and the layers generated from previous program. The overall program is shown in Figure 4-1.

![Figure 4-1. The implementation program in a CAD/CAM system](image)

Each phase of implementation program will be described using a pseudo code of each program. Even though the implementation is an integrated program, it can be explained into several different sections, where each of it is described using a pseudo code and the flow chart.

4.1 Phase I: Orientation Program Implementation

The following pseudo code describes the program for the case of cylindrical surfaces found in the 3D part model. Its flow chart is depicted in Figure 4-2.
Function FindCutVector 1

Input: part solid body

Output: possible orientation of the part with arc or cylindrical surfaces.

Begin

For i=0; i<number of arc/cylindrical surface; i++;
Candidate orientation = axis_i;
If axis_i // axis_i+1
Then orientation direction = axis_i;
Else no orientation direction;
End for (i);
Return orientation direction;

End
Figure 4-2. The flow chart for identifying cylindrical surfaces
The following pseudo code describes the case of planar surfaces found in the 3D part model. Its flow chart is depicted at Figure 4-3.

*Function FindCutVector 2*

Input: part solid body

Output: possible orientation of the part with a planar surfaces.

*Begin*

\[\text{For } i=0; \ i<\text{number of planar surface}; \ i++;\]

\[\text{Orientation direction 1} = \text{normal}_{i1};\]

\[\text{Orientation direction 2} = \text{normal}_{i2};\]

\[\text{Orientation direction 3} = \text{normal}_{i3};\]

*End for (i);*

*Return orientation direction;*

*End*
Figure 4-3. The flow chart for this algorithm for identifying planar surfaces
The following pseudo code describes the case of the parts having both cylindrical and planar surfaces in the 3D part model. As it is implemented, the program is using the same program as the two previous cases, but adding the surface checking routine before the beginning of the program.
Function FindCutVector 3

Input: part solid body

Output: possible orientation direction of the part with cylindrical and planar surfaces.

Begin

For i=0; i<number of surface; i++;
Check surface type;
If surface_i ==arc/cylindrical
Then Candidate orientation = axis_i;
   If surface_{i+1} ==arc/cylindrical && axis_i // axis_{i+1}
      Then orientation direction = axis_i;
   If surface_{i+1} ==planar
      Then orientation direction = axis_i;
If surface_i ==planar
Then Candidate orientation 1= normal_{i1};
   Candidate orientation 2= normal_{i2};
   Candidate orientation 3= normal_{i3};
For j = 1, 2, 3
   If surface_{i+1} ==arc/cylindrical && candidate_orientation_j // axis_{i+1}
      Then orientation direction = axis_{i+1};
   If surface_{i+1} ==planar
      Then orientation direction_j = candidate-orientation_j;
End for (j);
End for (i);
Return orientation direction;

End
4.2 Phase II: Slicing Implementation

The phase II of the program is to implement the slicing process, which transforms the part into layers. The following pseudo code describes the slicing algorithm using the possible orientation directions found. Its flow chart is depicted in Figure 4-5.

**Function GetSlice**

Input: CAD model and possible orientation direction

Output: sliced model into layers

**Begin**

```
For i=0; i< orientation directions; i++;
   For j=0; j<( surfaces // orientation direction); j++;
      Origin\(_j\) = Get origin point j;
      V\(_j\) = Projection of Origin\(_j\) to the orientation direction\(_i\);
      Possible slicing position\(_{i,j}\) = V\(_j\);
   End for (j);
End for (i);
Return slicing position;
Return Layer thickness;
```

**End**
For $i = 0, i < nFace$

$VnC = Face[i] \rightarrow \text{GetNormalFace}$

No

$VnC \parallel VnCut$?

Yes

$PtOrigC = Face[i] \rightarrow \text{GetOriginPoint}$

$PtProj = \text{Project}(PtOrigC, VnCut)$

$Vt = \text{Set}(StartPt, PtProj)$

$Zc = Vt \rightarrow \text{GetLength}$

$Found = FALSE$

Yes

$Zc = Z_{\text{Array}}[k]$?

No

For $k = 0, k < n && !Found$

$Found = Zc = Z_{\text{Array}}[k]$?

Yes

$Found = TRUE$?

No

$Z_{\text{Array}}[n] = Zc$

$Zc < Z_{\text{min}}$?

Yes

$Z_{\text{min}} = Zd$

No

$n = n + 1$

SORT $Z_{\text{Array}}$

Figure 4-5. The flow chart for the slicing algorithm
4.3 Displaying an Output

The output of implementation program is displayed as in Figure 4-6. This window will be shown next to the part in the CAD/CAD system environment. It shows the cutting vector(s) and the layers it generated after running the slice routine.

![Cutting vector display](image)

Button to activate the slicing process

Displaying the result

Layers display after slicing process

Figure 4-6. Implementation program display

4.4 Example Parts

The program was tested using two sample parts. Sample Part 1 (see Figure 4-7) contains only planar surfaces, which then generates the three possible orientation directions. Another part, Sample Part 2 (see Figure 4-11), has both planar and cylindrical surfaces, which generates only one possible orientation
direction. These possible orientation directions are depicted as an arrow in the part
drawing. The layers are displayed as an exploded view, as pictured in Figures 4-8,
4-9, 4-10, and 4-12.
4.4.1 Part 1

Figure 4-7. Sample Part 1
Figure 4-8. Alternative 1 of Layering Scheme for Part 1

Figure 4-9. Alternative 2 of Layering Scheme for Part 1
Figure 4-10. Alternative 3 of Layering Scheme for Part 1
4.4.2 Part 2

Figure 4-11. Sample Part 2
Figure 4-12. Layering scheme for Part 2
Chapter 5 Validation

The orientation and slicing algorithms and programs are validated using three real MECS devices: (1) a heat pump device, (2) a biodiesel device, and (3) a biodialysis device. As those devices are currently designed layer by layer, the development of the final device in a 3-D solid model is necessary for the program to be applied. The current layer design for each device is used for comparison to the layers resulting from the program.

The devices selected have different internal feature compositions. The heat pump consists of several functional features: a heat exchanger, a boiler, chamber, and a mixer that when assembled together build one device. In term of the features being considered in the algorithms, the heat pump device contains all through-cut features. The biodiesel and the biodialysis device each consist of an array of microchannel plate designs. The microchannel design of the biodiesel device contains combination of through-cut and non-through-cut features, while the microchannel design of the biodialysis contains all non-through-cut features.

The features in each device introduce a number of interesting issues for the algorithm in real application. Even though the algorithms are primarily designed to solve the through-cut features, it also can handle the non-through-cut features to some extent. By using those three real MECS devices, it is shown that the algorithms can be used to variety of other MECS devices.
The devices are shown as 3-D solid models, as are its resulting layers after the algorithms and program are applied. For clarity, all internal features of the devices are shown inside a transparent body.

5.1 The Heat Pump Device

The heat pump device is used as mini cooler and utilizes the same principles as refrigerator. This is the possible heat pump design, which consists of two heat exchangers, one boiler, one chamber and one mixer. The liquid will come through the input channel and will be processed in the heat exchangers and boiler, mixed in the chamber and mixer. Several output channels will be provided to let vapor out.

5.1.1 The Device

The components of the heat pump device are designed in a form of series of microchannels. In order to prevent thermal conduction between the components, a series of thin walls are put between them. The 3-D model of the heat pump with its internal features is shown in Figure 5-1 and its top view is in Figure 5-2.
Figure 5-1. The heat pump device

Figure 5-2. The top view of the heat pump device
5.1.2 The Result

The resulting layers for the heat pump device are shown in Figure 5-3. The program sliced the heat pump device into seven layers that contains all through-cut features. The lowermost and the uppermost layers are the caps. The five layers between the caps are the device. The resulting layers are the same as the layers designed by the original designer.

Figure 5-3. The sliced heat pump device
5.2 The Biodiesel Device

The biodiesel device is used to convert the vegetable oil and alcohol into the biodiesel. This mechanism is designed within a plate, which has two channel inputs, each for vegetable oil and alcohol. The channel sizes for these inputs are designed so that certain required pressure drop will be met. The oil and alcohol then will go through and be mixed into the reaction channel, which has length that allows the reaction to be completely performed. The output is the biodiesel and byproducts, which will go separately into different output channels.

In order to produce the required quantity of the biodiesel, more than one plate will be used in one device. The objective is to use as many microchannel plates as possible, but for the experiment and validation purposes, only up to three plates will be used.

5.2.1 The Device

The biodiesel device used for validation consists of three sets of microchannel plate design, where each plate has the same design and is arranged vertically within the device. The 3-D model of the biodiesel device with its internal features is depicted in Figure 5-4. The device top view in Figure 5-5 shows how the biodiesel microchannel plate is designed. And its side view is shown in Figure 5-6.
Figure 5-4. The biodiesel device

Figure 5-5. The microchannel plate design of the biodiesel device

Figure 5-6. The side view of the biodiesel device
5.2.2 The Result

The resulting layers for the biodiesel device are shown in Figure 5-7. The program sliced the biodiesel device into eleven layers. It sliced each microchannel plate into three different layers. Hence, the device itself has nine layers and two layers of caps at the lowermost and uppermost.

The resulting layers for the biodiesel device are slightly different from what has been designed by the human designer. In the original design, each microchannel plate is designed into one separate layer, instead of three different layers. The difference comes from the fact that the biodiesel channel design has a closed loop (circular) through cut feature. In order for the program to be applied to such a design, some adjustment is needed to the non through-cut features. The adjustment is to convert the non-through-cut into a through-cut feature without changing the functional requirement of those features. This adjustment results in a different layer composition.
Figure 5-7. The sliced biodiesel device
5.3 The Biodialysis Device

The biodialysis device uses the same principle of traditional hemodialysis, which is used to separate impurities from the blood. The device has two microchannel plates and one thin membrane as a filter. The blood will go through the first plate and then will be filtered through the membrane. The result is the blood without impurities that will go to the second plates.

Each plate has the same design, which has several channels in it. In its application these plates will be arranged so that the blood will go through smoothly and there will be no blood mixed between the plates.

5.3.1 The Device

The biodialysis device used for validation consists of three sets of microchannel plate design, where each plate has the same design and is arranged vertically within the device. The 3-D model of the biodialysis device with its internal features is depicted in Figure 5-8. The top view of the microchannel plate design and its side view are shown in Figure 5-9 and in Figure 5-10. Each set of the biodialysis microchannel plate consists of two channel plates, which are oriented in different directions with a thin membrane between them.
Figure 5-8. The biodialysis device

Figure 5-9. The microchannel plate design of the biodialysis device

Figure 5-10. The side view of the biodialysis device
5.3.2 The Result

The resulting layers for the biodialysis device are shown in Figure 5-11 below. The program sliced the biodialysis device into 19 layers. Each microchannel plate is sliced into two layers. Hence, for one set of microchannel plate it consists of four channel layers, two of which are at an opposite direction, and one membrane layer.

The biodialysis device is also sliced differently from the original design. Originally, each plate is designed into one separate plate. This also comes from the fact that it contains all closed loop cut or non through-cut features. In this case, these non-through-cut features will not be converted into through-cut features, in order to show how the algorithms react to the situation.

Even though it can be sliced, some of the layers are infeasible, because there are some features that are not connected to each other and form ‘floating’ features. The close up view of the infeasible layers is shown in Figure 5-12. These floating features will not be able to be manufactured properly, so that some further adjustment will be needed.

The adjustment is to make the infeasible layer into feasible layer by combining two or more layer into one new feasible layer. The infeasible layer can be combined or attached to its closest upper or lower neighbor layer. This combination process will be done until the sliced device contains all feasible layers.
Figure 5-11. The sliced biodialysis device
5.4 Analysis

The orientation and slicing algorithms works well for the real MECS devices with some limitations. The algorithms are designed to find the through-cut features and slice it according to their height. For a device that has all through-cut features, it will produce all feasible layers. Otherwise, the algorithms result in some additional feasible layers and/or infeasible layers.

The additional layers may be good for feature accessibility during layer manufacturing, but it may increase the manufacturing cost, as more layers need to be produced. The infeasible layers have to be remedied by either changing the
channel design or making it feasible. Further adjustment will be needed for the inexorable layer to be able to be manufactured. Two or more consecutive layers may be combined together to form one new layer. Currently, this can be done manually within the program after the slicing process is performed.

Within the program environment, there is an alert system to let the user know if there are one or more infeasible layers contained in the device. Every layer has a parameter of number of body, which indicates whether the layer consists of one solid entity or more. If the layer consists of one solid entity or body, it means that it does not have any ‘floating’ features. In other words, a feasible layer will have number of body = 1, and an infeasible layer will have number of body >1. For display, the layer information line will turn red to indicate the infeasible layer.

To obtain all feasible layers within a device, then the next objective is to make the number of body of every layer = 1. Currently, this can be done manually within the program after the slicing process is performed. Two or more layers can be selected to be combined into one new layer.
Chapter 6 Discussion

A computerized system for the orientation and slicing process of the microlamination process has been developed. It uses the final design of the part desired, and it performs the orientation and slicing process to the final design model in order to help plan to build the part.

As some limitations may occur in this computerized design system, this approach also offers some benefits over the current system. The system allows the designer to design the device more freely without having to be confined by the individual layer design. From the final device design, it can predict the manufacturability of the design in a term of number of layers, layers composition, and individual layer complexity. The design verification and possible design changes can be done much faster and more accurately.

As an automated pre-process planning, the system provides a significant stepping-stone to develop a fully automated process planning for the microlamination process. By utilizing the layers information provided by the program: layer configuration, layer thickness, and number of layers, it is easier to build the manufacturing process plan from the part design automatically.
6.1 The Algorithms

The algorithm that was developed utilized the similarity between the microlamination process and the layered manufacturing that is mostly used in the rapid prototyping process. While using the same orientation and slicing principles, it applies differently in the microlamination process.

In the microlamination, the orientation is used to find the best orientation according to the features contained in the part. The best orientation is selected to minimize the possible turbulence in the channel that might occur due to the presence of certain feature type (in this case cylindrical surface) and to prevent the lamination process (bonding process) to be done in a costly manner. Also, an orientation process developed for the microlamination process is used to cut or sliced the part into layers, instead of to build the part from layers as in the layered manufacturing.

The slicing algorithm is developed to slice the part into layers; so as each layer will be composed of set of through-cut features. The layers with through-cut features will increase the accessibility to manufacture the features, especially for the part, which contains internal features.

The input needed to run the system is the final design of the part in a CAD 3-D solid model. The major advantage of this system is that it uses the solid model directly without any further changes in its format. The output is set of layers that
need to be manufactured to build the final part. These output layers are in a solid model, which can be used for documenting or further processing.

The algorithm is developed to analyze the internal features contained in a part. These features determine how the part will be oriented for it to be sliced into layers. There are some feature interactions that may occur in a part. These interactions are not necessarily a physical interaction in which certain feature is connected directly to another feature, but there are positions and location interactions, which will affect the decision made during an orientation and/or slicing process.

Some rules have been devised for the orientation and slicing process. In developing the orientation algorithm, the feature’s attribute of surface type, normal direction of the surfaces that made up a feature, and/or the axis of a surface is mainly used to evaluate the feature interactions within a part. The surface type will determine whether it has an axis vector or a normal vector. The normal or axis direction of a surface will determine whether a certain feature is parallel, perpendicular, or non-parallel and non-perpendicular to another feature in a part. The first rule is that a feature that has a planar surface can be oriented in three direction, x, y, and z. The second rule is that a feature that has a cylindrical surface can only be oriented in one direction, which is along its axis. The third rule is that the cylindrical feature takes precedence than the planar feature.
In the slicing algorithm, the normal direction of a surface along the cutting vector or the orientation direction is mainly used to determine the cutting or slicing position of a part. The rule for slicing is that when there is only one feature found along a cutting vector, the feature will not be cut through, but if there is more than one different feature, the cutting layer thickness will depend on the lowest height among those features. This rule will result in some features may be sliced into several layers, while other features may not be sliced at all, which means that one layer will contain the whole feature.

The algorithm has been integrated into the SolidWorks CAD/CAM system. While trying to maintain the independency of the algorithm, some adjustments are still needed when implementing the algorithm. The adjustments are mainly related to extracting the part information into the format, which is required by the algorithm.

6.2 The Implementation

The algorithms work well for the real MECS devices with some limitations. It only results in all feasible layers when the device contains all through-cut features. It results in infeasible layers when all non through-cut features or a combination of through-cut and non through-cut features are present in the device.
Some adjustments may be needed to change the infeasible layers into feasible ones. The adjustments may be in the feature level or layer level. The non-through-cut features may be adjusted so that the resulting layers are still feasible. Or, the adjustment may be done by combining two or more layers into one new layer. These adjustments currently have to be done manually.
Chapter 7 Recommendation

As the algorithms developed are able to solve some problems in microlamination, some limitations have been observed during its application. Therefore, further research and exploration is recommended to enhance its application in the future. The recommendation suggested is described below.

7.1 Current Research

Additional rules may be added to accommodate the presence of the closed loop cut features in a part. The resulting infeasible layer may be chosen, and a new rule can be developed to determine whether this infeasible layer is going to be combined with its lower or upper layer or both.

The current algorithms are developed based on features, which have certain surface types: planar and cylindrical surfaces. Although these types of surfaces are able to represent many applications, there may be some designs that need more elaborate and complex representation that is not supported by those surfaces. For these designs, further exploration will be needed to accommodate their needs.

7.2 Future Research

For future research, it is recommended to develop a complete automated process planning for microlamination process. By taking the layers composition
and a layer manufacturing knowledge as an input, the layer process selection rule can be developed. The result, then, can also be linked automatically to the manufacturing facility.

Additional important information that can be considered in developing the complete process planning system is the material information for each layer. As the program is used to design a device, it does not take into account the possibility that the device could be built by different material for each of its layers. It put the emphasis only in the device geometry. A different material for a certain layer may add more restriction to its layer design and possibly to its neighboring layer, so that it would affect the slicing algorithm.
Bibliography


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