An Analytic Framework for Developing Inherently-Manufacturable Pop-up Laminate Devices

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Abstract.
Spurred by advances in manufacturing technologies developed around layered manufacturing technologies such as PC-MEMS, SCM, and printable robotics, we propose a new analytic framework for capturing the geometry of folded composite laminate devices and the mechanical processes used to manufacture them. These processes can be represented by combining a small set of geometric operations which are general enough to encompass many different manufacturing paradigms. Furthermore, such a formulation permits one to construct a variety of geometric tools which can be used to analyze common manufacturability concepts, such as tool access, part removability, and device support. In order to increase the speed of development, reduce the occurrence of manufacturing problems inherent with current design methods, and reduce the level of expertise required to develop new devices, the framework has been implemented in a new design tool called popupCAD, which is suited for the design and development of complex folded laminate devices. We conclude with a demonstration of utility of the tools by creating a folded leg mechanism.

1. Introduction

There has been a proliferation of new technology surrounding laminate manufacturing in recent years, in which designs are based upon mechanisms which can be created from primarily planar operations such as cutting, folding, and laminating flat sheets of multiple materials together. These devices are typically developed at a scale larger than that of traditional Micro Electro-Mechanical Systems (MEMS), but where conventional assembly of prefabricated components is still quite difficult. There are different names for this paradigm, including Printed-Circuit MEMS (PC-MEMS) [33,38], Smart Composite Micro-structures (SCM) [21,39], Printable Robotics [11,28], and Lamina-Emergent Mechanisms (LEM) [18,22], but they all share aspects of an overarching theme: material is selectively added and removed layer by layer to create complex devices. Material-removal processes often utilize bulk material removal processes or rapid-prototyping tools such as lasers, which permit a level of complexity in terms of geometry and kinematics otherwise difficult to achieve. The utilization of layers with varying material properties can create a variety of mechanical elements, including structural elements, flexible hinges, rigid connections, and springs, which can form complex three-dimensional geometries when folded or erected into their final shapes [1, 5, 22]. A variety of sensing [13, 14, 20, 30] and actuation [17, 24, 40] strategies are also compatible with this paradigm. Figure 1 shows just a few examples of these devices.

In order to permit the more widespread adoption of this powerful new prototyping and fabrication method, the purpose of this article is to lay out a set of procedures that will simplify the design and process planning. The similarities among these manufacturing paradigms within the individual processing steps permits us to define a general and unified manufacturing process. This process can be used for making small or meso-scale complex electromechanical systems that combine kinematic functions, electronics, sensing, and actuation. We accomplish this in several steps. First, we formally define the various material addition, removal, and lamination operations mathematically so that the process of creating a new device can be composed into a formal manufacturing plan. Second, we condense the physical constraints and limitations of manufacturing into a set of rules which can be used to check the validity of a given plan. These formulations allow the creation of design algorithms, manufacturing checks, and commonly-used mechanical structures which facilitate rapid development. These tools are incorporated in a new software suite we are developing called popupCAD.

With this rigorous definition of the process one can envision several developments. By building a limited set of well-defined manufacturing operations, design rules, and manufacturability checks we can envision the creation of component libraries which can be shared between designers and manufacturers. Such libraries, based on a relatively small set of manufacturing rules all common to this generic PC-MEMS process, could facilitate more-rapid development of devices which are inherently manufacturable across a wide range of physical material addition, removal, and adhesion processes. Common rules, libraries, and designs are also a necessary precursor to the development of a mechanical foundry system, just as the Carver-Mead design rules for VLSI Development spawned the creation of MOSIS [7], and which were also mirrored to a smaller extent in the field of MEMS. In these cases designers were willing to sacrifice optimal designs in terms of weight, specific strength, or component spacing in order to develop devices compatible with the available manufacturing processes.

1.1. Background

Other design paradigms share similar manufacturing processes and design challenges. The emerging field of printable robots utilizes origami-like folding techniques to build three-dimensional devices from flat sheets, with the aim to eventually enable low-cost and widely accessible fabrication of complex devices. These structures have traditionally

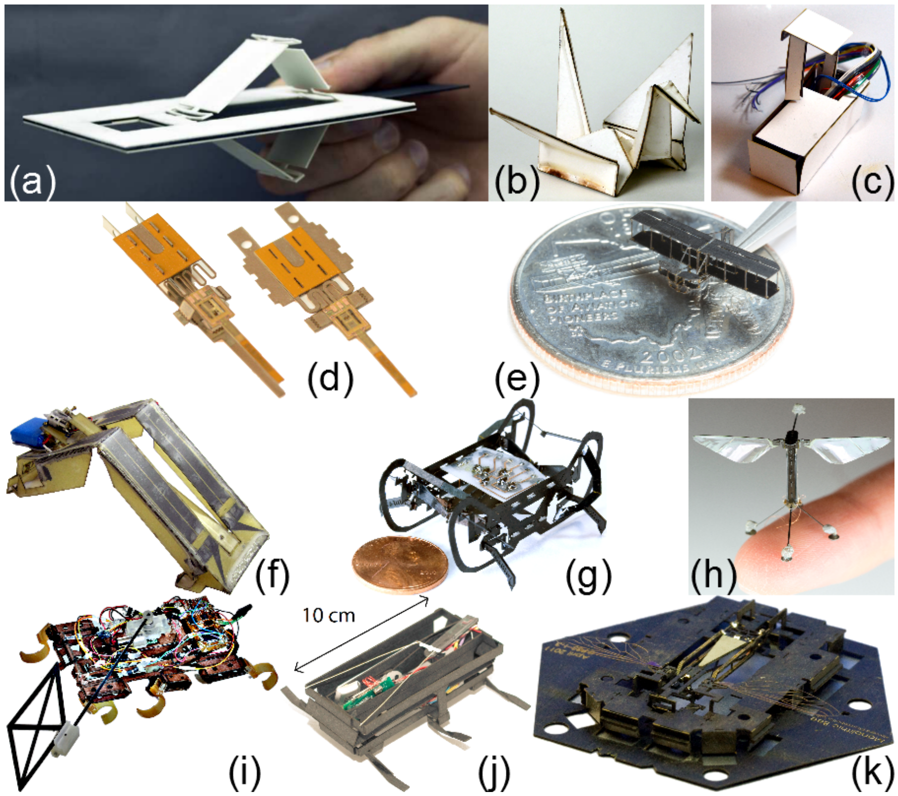

Figure 1. Many Devices Built with Laminate Manufacturing Techniques. (a) Multi-layer Lamina Emergent Mechanism [18] ©ASME; (b) Self-Folding Paper Crane [11], ©S. Felton; (c) Self-Folding Light [31]; (d) Sensing Surgical Gripper [15], ©J. Gafford; (e) Wright Flyer [38], ©K. Ma; (f) Self-Folding Inchworm [10], ©S. Felton; (g) HAMR VP [2], ©A. Baisch; (h) RoboBee [27], ©K. Ma; (i) SailRoACH [25], ©N. Kohut, UC Berkeley; (j) DASH [5], ©P. Birkmeyer, UC Berkeley; (k) Mobee [33], ©P. Sreetharan.

capitalized on folding algorithms derived from the field of computational origami to create such shapes without complex laminate structures [16, 29]. Recent work has increased the complexity of printable composites by adding specialized features and layers to facilitate self-assembly and embedding of control circuitry and components [11, 26, 34].

Despite the benefits associated with scaffold-based manufacturing for pop-up devices [33] and self folding paradigms [11] for printable robots, the development time for such devices remains long. This is due to a number of reasons. As the number of layers and sub-mechanisms grow within a single device, so does complexity, leading to longer development times. The tedious design process is due in part to the absence of design software tailored to this new manufacturing paradigm. Commercial CAD software like Solidworks‡ deals primarily with the geometry of three-dimensional solid bodies to define parts, assemblies, and their kinematic connections. While it includes features and plugins specific to weldments, molds, and sheet metal, it does not include features specifically applicable to PC-MEMS, and the process for developing stacked,

‡ http://www.solidworks.com/

two-dimensional geometries therefore falls back to more traditional workflows associated with drawing three-dimensional shapes. Generic CAD programs generally do not examine parts for manufacturability, requiring designers to internalize the assembly and manufacturing rules during when designing parts. As a consequence, designers minimize design complexity and resort to manual location and assembly operations to accommodate easier-to-design sub-components. This dependence on hand fabrication results in manufacturing defects and longer assembly times due to alignment and gluing steps which would be obviated by assembly scaffolds and self-folded structures.

In parallel to the solid-modeling approach taken by many commercial CAD applications, research into folded origami-like structures has also produced design software mainly in the research community§ [35]. Research into such structures, however, is often focused more on producing three-dimensional shapes rather than mechanisms. Such research often assumes single layer sheets with zero thickness, and usually does not consider other manufacturing processes such as cutting and gluing.

1.2. Similar Manufacturing Technologies

	PC-MEMS	SDM	3D Printing	Sheet Metal Fabrication
Discrete Layers	y		y	y
Number of process loops	many	many	1	1
Material Removal	y	y		y
Material Addition	y	y	y	
Adhesion	y	y	y	y
folding / bending	y			y
Locking	y			
Surface Preparation	y	y		
Alignment	y	y	y	y
Multi-Material	y	y	y	
Embedded Components	y	y		
Curing	y	y	y	

Table 1. Manufacturing Capabilities by Manufacturing Method

A variety of rapid prototyping processes must also weigh the cost of design complexity vs. manufacturing simplicity (see Table 1). These technologies must often deal with the concept of material support and removal, for example. To solve this problem, 3D Printers often use two materials for the printing process. One material ultimately becomes the device, and the other material supports the device from above or below as each layer is added, only to be broken, dissolved or melted away after fabrication is complete. In contrast, PC-MEMS devices are often supported from the

§ www.langorigami.com/science/computational/treemaker/

sides by the same layers of material which make up the final device. This material location constraint limits how devices can be supported.

Other manufacturing technologies have similar iterative assembly processes involving bending and folding. Origami, Sheet Metal Fabrication [36], and some MEMS devices [41] utilize folding and bending to form three-dimensional devices. This process can be limited by part interference; thus, achieving the correct fold sequence and even planning a design to ensure foldability becomes a concern.

Some rapid-prototyping processes are inherently iterative. Shape Deposition Manufacturing(SDM), for example, uses sequential material addition and removal steps to iteratively build multi-material devices with embedded components [6, 37]. It has been used to create a number of complex electromechanical devices, including robots [8, 32] and haptic devices [3]. Like PC-MEMS, the SDM manufacturing sequence is driven by the physical constraints of the process; material addition is generally accomplished by a polymer casting step and removal is often performed with CNC milling. These processes limit the material geometries which can be cast and removed in a single iteration of the manufacturing process. From these limitations, process planning strategies have been developed to enable splitting of SDM manufacturing processes into inherently-manufacturable sub-components [4, 19].

The study of assembly (and disassembly) planning for general three-dimensional geometry has also been studied extensively, as surveyed in [23], and has generated a number of concepts about connectedness, removability and assembly sequencing which can be applied to the specific geometries and processes present with PC-MEMS. Its study has resulted in a number of planning routines implemented in software, closely tied to the field of path planning. This ability to generate an inherently manufacturable process plan for pop-up devices motivates the following analytical framework.

2. Overview of PC-MEMS

The PC-MEMS manufacturing process outlined in Figure 2 is a series of iterative material addition and removal sequences that can be split into two main cycles. In the first series of steps, layers of functional materials are individually cut into patterns and laminated together, forming a composite structure whose many functions are derived from the properties of each individual layer and the interaction between all layers in the laminate. The second cycle consists of material removal, assembly, and locking steps, where scrap is removed and the device is erected and locked into its final position and then freed from the surrounding support material.

2.1. Laminate Layup Steps

2.1.1. Layer Cutting and Surface Preparation Prior to lamination, material is removed from each layer to assist in identification or alignment, to remove rough edges from sheet stock, and to eliminate geometries which will not be removable after lamination. Many

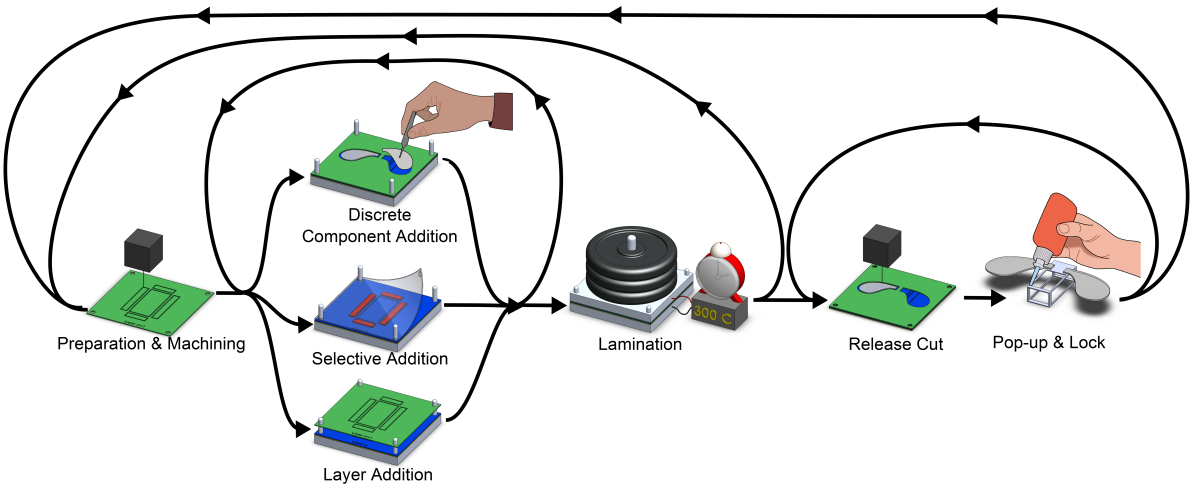

Figure 2. PC-MEMS Process Diagram

different material removal methods are supported, from cutting operations performed by plotter-style vinyl cutters, wire EDM, or lasers, to more volumetric machining processes such as milling, etching, and bulk micro-machining. The choice of laminate materials affects which cutting operations are supported, how many layers can be cut at a time, the width and depth of the cut, surface quality and finish, as well as the tolerances of the geometries.

In order to prepare the surface for subsequent bonding to neighboring layers, a variety of surface treatments such as chemical etching can also be applied to the layer to promote adhesion. Materials also often carry a surface charge, making them difficult to handle. A layer can become attracted to itself and inadvertently curl or stick to neighboring layers. A de-ionizer is used in these cases to remove as much of this surface charge as possible.

2.1.2. Bulk Material Addition Once prepared, each sheet of pre-cut material is laid in a jig, consisting of two or more pins used to align layers, with patterned adhesive interleaving between most layers of functional material, as shown in Figure 2. This is currently a manual operation, using tweezers to carefully align material onto pins that serve as persistent alignment features through the lamination process. At larger scales, this could be automated with a pick-and-place or roll-to-roll process, as with printed circuit boards.

The palette of materials used in the layup varies substantially across manufacturing paradigms, as seen in Table 2. Structural layers may consist of materials like paper, cardboard, polymer sheets reinforced with fiberglass or carbon fiber, or metal. Flexible layers are included to create kinematic joints, used later in the assembly steps or in the final mechanism. Flexible layers such as polyimide can also be patterned with copper traces, allowing for power or circuitry to be routed between moving parts. A variety of adhesives may be used to attach these layers together, and can either be applied directly to materials' surface or treated as separate layers, and the process itself can be repeated indefinitely with arbitrary numbers of layers and components.

2.1.3. Selective Material Addition As mentioned in [38], "mechanical vias" can be used to create rigid connections across layers to connect bodies in complex ways. These vias must often be selectively placed in specific regions between neighboring layers. This is often accomplished by using an applique process where aligned islands of material are attached to a backing sheet with a light adhesive. This backing sheet contains alignment and identification geometry, and is used to align the material islands to the existing layup. These materials are subsequently "back-tacked" to the laminate with a stronger adhesive that holds the applique in place. The backing material is then peeled away, leaving the applique behind. Other material addition methods such as patterned-deposition or lift-off processes can be envisioned using similar techniques.

2.1.4. Component Addition Discrete components may be added to the growing laminate. This may be due to components being sensitive to the machining or laminating operations, because geometric limitations would dictate component interference with a cut path, or because they are produced via another process. Examples include components such as electrical IC's, motors, sensors, or brittle materials.

For large-scale manufacturing, component addition steps may be performed just as board-stuffing machines are used in the PCB fabrication process to place many individual components at the same time. This is facilitated by the planar nature of the laminate fabrication process, which enables massive parallelization of assembly steps by way of duplicated arrays of mechanisms all being manufactured at once. For small batches, hand placement of parts can be facilitated by planar kinematic alignment features, planar springs, and assembly scaffolds to ensure high precision during placement [33].

The main difference between component addition and selectively applied layers is that components are often incompatible with other manufacturing processes – i.e. should not be cut once applied – whereas selectively applied material can generally be included in subsequent cutting and removal steps.

2.1.5. Lamination Thermoset adhesives are often used to make aligning and stacking operations more manageable, as such adhesives are not very sticky prior to a separate curing step. These adhesives come in sheets‖, allowing them to be cut, handled, and treated as separate layers, usually interleaved between the other layers of material. Thermoset adhesives permit the stack to be aligned and adjusted without fouling prior to lamination, which is accomplished with a temperature and pressure-controlled platen press.

‖ Dupont's Pyralux FR Adhesive can be found at `www.dupont.com`

2.1.6. Lamination Process Iteration The sequence of material removal, addition and lamination can be repeated on the evolving laminate. The sequential nature of these operations allows designers to embed components and create complex emergent geometries before ever removing the final laminate device from its outer support structure. This permits the reuse of alignment and identification geometry throughout the process, maintaining precise tolerances even after part handling steps.

	RoboBee [9]	SailRoACH [25]	Inchworm [10]
Structural	Carbon Fiber, Titanium	Cardboard	PEEK
Flexure Hinge	polyimide	PET	Polyimide & PEEK
Adhesive	Acrylic sheet adhesive	Hot melt adhesive	Silicone Tape
Damping	N	Urethane “C” Legs	N
Assembly	Assembly Scaffolds	N	Self-Assembly via Pre-stretched Polystyrene & Embedded Heating Circuits
Electrical Conduction	Copper-Clad FR4, Carbon Fiber	Wires	Copper-Clad Polyimide
Locking Strategy	Tab & Slot, Glue	Glue	Not Necessary
Actuation	Piezo-Electric Actuators	DC Motor	DC Motor
Sensing Modes	Optical Flow Sensor, IMU	Accelerometer, Gyro, Motor Encoders,	N
Power	External	Lithium-Polymer Battery	External for Folding, Lithium-Polymer Battery for Motion
Length	30 mm	100 mm	226 mm
Weight	70 mg	29 g	29 g

Table 2. The materials, locking methods, and sensing and actuation modes used for three example devices made with the PC-MEMS, SCM, and Printable paradigms.

2.2. Release, Assembly, and Locking

A second set of operations is then iteratively applied once the final lamination step has occurred in order to remove the material used to support, align, and identify individual layers and free the device for assembly. In general, each moving part of the final device is supported from the surrounding web of material or internally with bridges of material which constrain the motion of the device. As each support is removed, new degrees of motion are exposed, allowing the emergent device to be assembled or erected into its final shape. Scrap is also generated as release cuts are performed. The removal of scrap from the device can expose new regions for cutting and can allow the emergent device to move more freely. The subject of removability, for both the device and surrounding scrap, is defined and studied in later sections.

As each new degree of freedom becomes available in the device by a release cut and scrap is cleared away, some parts must be assembled and permanently locked in place. Like component placement, this step can be accomplished by a variety of methods, from manual placement to automated, parallelized assembly procedures, facilitated by other devices and external machinery. Once the the assembly step is complete, the assembly degrees of freedom may be locked in place with glue, solder, etc. Like the lamination sequence, these steps may be repeated until the entire device is both assembled and released.

While the sections above describe, in general, the steps of the PC-MEMS process, it is only a high-level description of the many variations that could be imagined.

The devices which result can be inserted into other devices, allowing the process to continue on even higher levels. Compatible materials and processes may be grouped in advantageous sub-assemblies and merged later. Table 2 shows three different sets of compatible manufacturing materials and processes which are used together to build PC-MEMS-based devices at different scales.

3. Formal Definition of the Manufacturing Process

3.1. Introduction

There are some basic observations we can make about the PC-MEMS manufacturing process which will help us outline the framework for representing and analyzing its structure. As described in Section 2, PC-MEMS devices are composed of thin, discrete sheets of laminated material. These sheets are usually cut by a laser, with the ability to create fine geometries in the plane of the material, but without much control over the depth of cut. This observation allows us to represent the geometries of such devices as ordered collections of flat two-dimensional geometries, such as polygons, lines, and polylines.

3.2. Basic Definitions

3.2.1. Layers and Laminates A shape s is a closed, compact and bounded subset of $\mathbb{R}^2$. A layer, represented by capitalized, italic letters, such as L, is defined as a subset of planar Euclidian space $\mathbb{R}^2$, or

$$L = \left\{x : x \in \mathbb{R}^2\right\}. \tag{1}$$

A laminate is defined as an ordered set of layers of a finite dimension and represented by capitalized, bold letters, such as $\mathbf{L}$. In this paper we will assume that unless otherwise noted, laminates have dimension κ, where

$$\mathbf{L} = (L_1, \ldots L_\kappa). \tag{2}$$

This ordered set represents a sequence of layers corresponding to the ordering of material geometries in a mechanism. A different sequence of layers results in a different distribution of material, resulting in a fundamentally different mechanism. Both layers and laminates can be operated upon by their respective elements. The union, intersection, difference, dilate, and erode operations can be defined for layers:

$$A \cup B = \left\{x \in \mathbb{R}^2 : x \in A \text{ or } x \in B\right\} \tag{3}$$

$$A \cap B = \left\{x \in \mathbb{R}^2 : x \in A \text{ and } x \in B\right\} \tag{4}$$

$$A \setminus B = \left\{x \in \mathbb{R}^2 : x \in A \text{ and not } x \in B\right\} \tag{5}$$

$$A \oplus B = \left\{x \in \mathbb{R}^2 : x = a + b \text{ for } a \in A, b \in B\right\} \tag{6}$$

$$A \ominus B = \left\{x \in \mathbb{R}^2 : x + b \in A \text{ for } b \in B\right\} \tag{7}$$

Similar operations can be defined for laminates as well. Such operations are restricted to laminates of the same dimension

$$\mathbf{A} \cup^{\kappa} \mathbf{B} = (A_i \cup B_i)_{i \in [\kappa]} \tag{8}$$

$$\mathbf{A} \cap^{\kappa} \mathbf{B} = (A_i \cap B_i)_{i \in [\kappa]} \tag{9}$$

$$\mathbf{A} \setminus^{\kappa} \mathbf{B} = (A_i \setminus B_i)_{i \in [\kappa]} \tag{10}$$

$$\mathbf{A} \oplus^{\kappa} \mathbf{B} = (A_i \oplus B_i)_{i \in [\kappa]} \tag{11}$$

$$\mathbf{A} \ominus^{\kappa} \mathbf{B} = (A_i \ominus B_i)_{i \in [\kappa]} \text{, where} \tag{12}$$

$$[\kappa] = (1, \ldots, \kappa). \tag{13}$$

Layer A can also be promoted to a laminate using the $^{\kappa}$ operator, with

$$A^{\kappa} = (A_i : A_i = A \text{ for } i \in [\kappa]) \,, \tag{14}$$

which allows us to define an empty laminate $\mathbf{0}$ as

$$\mathbf{0} = \varnothing^{\kappa}. \tag{15}$$

Additionally, individual layers of a laminate can be selected with the *layer*() mapping, where for some for some $A_i \in \mathbf{A}$,

$$A_i = layer(\mathbf{A}, i). \tag{16}$$

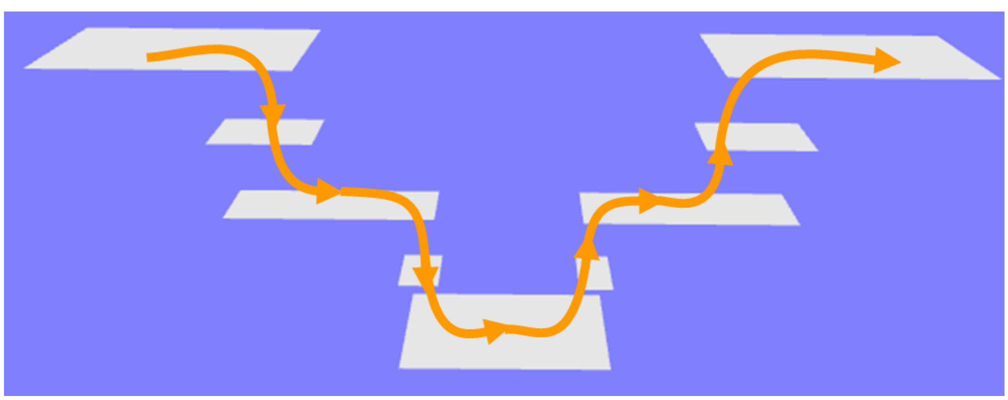

Figure 3. A Connected Laminate

3.2.2. Connected Laminates A layer $L_i \in \mathbf{L}$ produces a mapping $L_i \rightarrow s_1, \ldots s_n$ if its points can be collected into a compact set of non-intersecting shapes s_j such that

$$L_i = \bigcup_{s_j \in S} s_j \tag{17}$$

$$s_j \cap s_k = \varnothing \text{ for } \forall s_j \in S_i, \forall s_k \in S_i, j \neq k. \tag{18}$$

Laminates composed of such layers induce an undirected graph $G(\mathbf{L}) = (V, E)$ where each vertex $v \in V$ corresponds to some shape s_j in some layer $L_i \in \mathbf{L}$. For each vertex $v \in V$ we let $shapeof(v)$ be the shape to which v corresponds, and let $layerof(v)$ be the index to the layer which contains $shapeof(v)$. There is an edge $(u, v) \in E$ if and only if the following statements are true:

(i) $shapeof(u) \cap shapeof(v) \neq \varnothing$.

(ii) $|layerof(v) - layerof(u)| = 1$.

(iii) The layers to which u and v belong are physically joinable, e.g., one or the other is an adhesive.

We will say a laminate $\mathbf{L}$ is connected if and only if the induced graph $G(\mathbf{L})$ is connected. Figure 3 represents a connected laminate, with the highlighted path loosely showing how connections between polygons on different layers are established.

Regardless of whether a laminate $\mathbf{L}$ is connected or not, the mapping $connected(\mathbf{L})$ produces a set of laminates $\{\mathbf{L}_1, \ldots, \mathbf{L}_m\}$ such that each laminate is connected. In other words,

$$\text{connected}(\mathbf{L}) = \{\mathbf{L}_1, \ldots, \mathbf{L}_m\} \text{ such that} \tag{19}$$

$$\text{connected}(\mathbf{L}_i) = \mathbf{L}_i \text{ for } \forall \mathbf{L}_i \in \text{connected}(\mathbf{L}), \tag{20}$$

$$\mathbf{L} = \bigcup_{\mathbf{L}_i \in \text{connected}(\mathbf{L})} \mathbf{L}_i, \text{ and} \tag{21}$$

$$\varnothing = \mathbf{L}_i \cap^{\kappa} \mathbf{L}_j \text{ for } \forall i, j \in \{1, \ldots, m\}, i \neq j. \tag{22}$$

3.2.3. First Rule Of PC-MEMS All the points that will be used to produce a device can be grouped together in the term $\mathbf{B}$, where

$$\mathbf{B} = \mathbf{D} \cup^{\kappa} \mathbf{W} \cup^{\kappa} \mathbf{S} \cup^{\kappa} \mathbf{A} \cup^{\kappa} \mathbf{I} \cup^{\kappa} \mathbf{C}, \text{ where} \tag{23}$$

$\mathbf{D}$, $\mathbf{W}$, $\mathbf{S}$, $\mathbf{A}$, $\mathbf{I}$, and $\mathbf{C}$ represent the device, web, scrap, alignment, identification, and cut geometry, respectively. If each layer starts from a continuous sheet of material, then

$$\mathbf{B} = \text{ConvexHull}\left(\bigcup_{B_i \in \mathbf{B}} B_i\right)^{\kappa}. \tag{24}$$

This concept can be important for large-scale planar processes, allowing designers to calculate and compare the material efficiency of competing designs. $\mathbf{B}$ also represents the starting point for manufacturing, as the materials usually start the process in the form of rolls or sheet stock, whose scale, when compared to a single device, is essentially considered continuous. This definition also sets the stage for many relations in the forthcoming sections, as the concepts of material removal and connectedness can be applied to determine optimal strategies for scrap removal, material support, and device assembly.

3.2.4. Material Definitions A device $\mathbf{D}$ may be defined as a connected laminate whose layers contain all the points which make up a desired mechanism, or

$$\mathbf{D} = (D_i)_{i\in[\kappa]}\,. \tag{25}$$

While the device may be as little as one layer thick, flexible, or consisting of many multi-layer segments, these segments must all be connected to form a single unit. Scrap $\mathbf{S}_i$ is any laminate object discarded during the manufacturing process, and is generally a by-product of cutting operations. A common design error leads to situations where it is difficult or impossible to remove scrap because it becomes trapped inside other layers as a result of iterative cutting and laminating procedures. It is therefore important to be able to identify these islands of scrap material and determine whether they can be removed during particular steps of the cutting process. Together, the n individual pieces of scrap can be grouped into the laminate $\mathbf{S}$, where

$$\mathbf{S} = \bigcup_{i\in(1,\ldots n)} \mathbf{S}_i, \text{ and} \tag{26}$$

n represents the number of individual pieces of scrap laminate. This is related to disassembly planning (or assembly planning by disassembly planning) in the literature.

The web, $\mathbf{W}$, is scrap which surrounds and supports a mechanism prior to its final removal. Web material is composed of the same layers which make up the final device, and can itself be designed to further optimize the manufacturing process. There are fewer restrictions on the web, however, because it is discarded after its role in the manufacturing process is complete.

Alignment geometry A will be necessary to help align layers for both cutting and lamination steps. In its simplest case, proper alignment can be accomplished by aligning the outer edges against a flat surface. In other cases, alignment pins can be used to constrain and locate layers during the cutting and laminating steps. Some steps may not support physical alignment of material, and rely instead on proper alignment and calibration in software. In general, common alignment geometry A is included in the first cut so that subsequent placement operations can refer to those original locating marks to maintain precision.

$$\mathbf{A} = A^{\kappa} \tag{27}$$

Identification geometry, I_i, is another important piece of geometry which should be applied to each layer to help identify and orient that material. Often, geometry can appear symmetric when not, resulting in manufacturing mistakes where layers are laminated upside-down or rotated. This can be prevented by providing asymmetric alignment geometry compatible with only one orientation. When this is unavailable, text or registration marks can be used to identify layer sequence and orientation.

$$\mathbf{I} = (I_i)_{i\in[k]}. \tag{28}$$

3.3. Manufacturing and Manipulation steps

3.3.1. Material Removal Material removal is represented by the difference operator ($\setminus$), which is used as a binary operator between two layers. For example, $A \setminus B$ indicates the removal of the material in layer B from that in layer A. Material removal can also be applied to laminates, and is applied according to Equation (10), so that $\mathbf{C} = \mathbf{A} \setminus^{\kappa} \mathbf{B}$ represents the material removal of laminate **B** from laminate **A**, which results in **C**. The difference operator does not consider the method of removal in itself. Removal could be accomplished by bulk machining, cutting, or disassembly processes.

Regardless of the method, the material removed can be represented in the layer by C, the collection of points in $\mathbb{R}^2$, and in the laminate with the equation

$$\mathbf{C} = (C_i)_{i \in [k]}. \tag{29}$$

The purpose of material removal operations is twofold. First, these operations are used to remove the material contained in **C**. Mills can remove this material by performing pocket milling, i.e., the method of sweeping a mill across the entire area of material to be removed. Lasers are also capable of removing areas of material by rastering, a process similar to pocket milling.

The second purpose of material removal is to split a single connected laminate into multiple connected laminates for the purposes of subsequent separation and removal of one or more of these pieces. Scrap can be removed from a device in this manner without having to machine the entirety of geometry contained in $\mathbf{C} \cup^{\kappa} \mathbf{S}$. The advantage of using material removal for this purpose is that because pocket milling or rastering operations can be time-consuming – with the amount of time required to remove a certain volume of material proportional to the square of a nominal dimension of the area – the concept of splitting and removing entire laminates can significantly reduce overall machining time.

3.3.2. Flipping Laminates may be flipped during part handling to expose the bottom layers to a machine tool or to prepare the surface for bonding. Flipping both switches the order of the layers as well as applies a transformation T to its geometry. This can be represented as

$$\mathbf{L}^f = (\mathrm{T} L_i)_{i \in (\kappa, \kappa-1, \ldots 1)}, \tag{30}$$

Flipping preserves vector lengths, vector angles, and layer order, and two successive flipping operations result in the original laminate, with

$$\mathbf{L} = \left(\mathbf{L}^f\right)^f, \text{ which requires that} \tag{31}$$

$$\mathrm{T}^2 = \mathrm{I}, \tag{32}$$

where I is the identity matrix.

3.3.3. Material Addition and Lamination Because of the requirements of the lamination process, material layers must be capable of attaching to other material layers either by the use of adhesive, or after a thermal, mechanical, or chemical operation which physically joins neighbors together. In the paradigm of PC-MEMS, alternating layers are typically composed of a thermoset adhesive which bond with neighbor layers on both sides.

There are several different types of material addition processes, as mentioned in Section 2.1. When one or more layers are added together, a new laminate is formed, consisting of the ordered sequence of layers in the two current laminates, as

$$\mathbf{C}_{(\kappa+\ell)} = (A_1, \ldots A_\kappa, B_1, \ldots B_\ell)\,. \tag{33}$$

where $\mathbf{A}$ is a laminate consisting of κ layers, $\mathbf{B}$ is a laminate consisting of ℓ layers, and $\mathbf{C}$ is the $(\kappa + \ell)$-dimension laminate formed from joining laminates $\mathbf{A}$ and $\mathbf{B}$, respectively. Single layers (L) can be added in the same manner after being promoted to a 1-dimensional laminate, or $L \rightarrow L^1$.

3.4. General Process Considerations

The above definitions have provided the framework for describing the geometry of laminate structures without considering the constraints associated with particular manufacturing processes. Material removal processes in particular are constrained by the issue of tool access: to cut a material, the material removal device must be able to reach the intended material. The corollary to this problem is the issue of material protection: whatever region of material the tool cuts must not infringe on material which must remain.

3.4.1. Machine Tool Access and Keep-out When material is removed from a laminate by machining processes, it can in general only be removed by tools whose cutting volumes extend from below or above the planes of the laminate and continue into successive planes of material.¶ On the other hand, lasers, with relatively poor control of their depth-of-cut, may often exhibit cutting volumes which extend completely through all layers of material.

Common milling operations are performed using cutting tools which exhibit a three-dimensional cut volume, relative to the diameter of the cutting tool and the cut paths they make through the material. Laser machining operations, on the other hand, can often be approximated with 2-dimensional cut paths; in this case the kerf (the width of material removed), often on the order of 10-20 μm, is considered negligible.

The keep-out region of a laminate is defined as the material which must not be accessed during a particular material removal operation, reflecting the geometric

¶ We assume that milling operations are only possible from "above", or the D_κ side, rather than the D_0 side of the device.

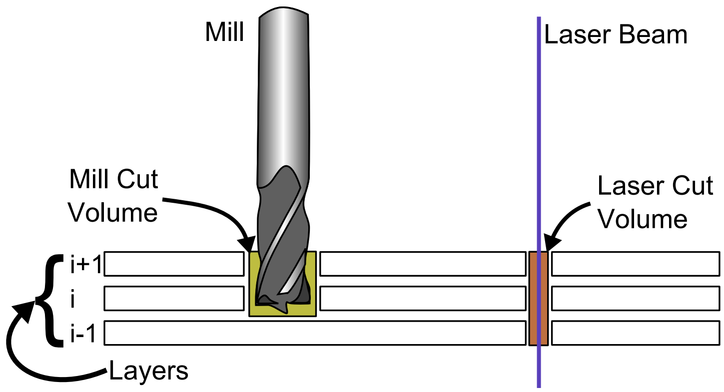

Figure 4. Cut Volumes for Milling and Laser Cutting

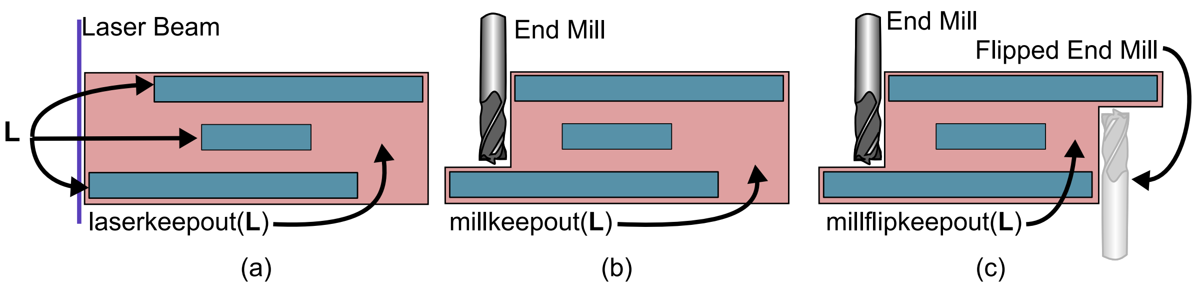

Figure 5. Three machining keep-out regions. A device **L** (in blue) produces different keep-out regions for (a) laser cutting, (b) machining, and (c) machining with flipping.

limitations of the machining process. Material contained within the keep-out region is preserved by the equation

$$\mathbf{L} = \mathbf{K} \cup^{\kappa} \mathbf{L}, \tag{34}$$

where **K** represents a keep-out region for laminate **L**. If **C** represents a desired cut, it follows that

$$\mathbf{0} = \mathbf{K} \cap^{\kappa} \mathbf{C}. \tag{35}$$

By checking all cuts against Equation (35) a keep-out region becomes a useful tool for preserving all the material contained within **L**, as when **L** describes the material of a PC-MEMS device.

If $\mathbf{A}_1$ and $\mathbf{A}_2$ represent the regions accessible by two material removal processes, $\mathbf{A}_1 \cup^{\kappa} \mathbf{A}_2$ represents the accessible region by both. Conversely, the two respective keep-out regions, $\mathbf{K}_1$ and $\mathbf{K}_2$, can be merged with the equation

$$\mathbf{K}_{merged} = \mathbf{K}_1 \cap^{\kappa} \mathbf{K}_2. \tag{36}$$

This implies that machine tool accessibility grows with an increasing palette of available material removal processes, shrinking the associated keep-out region.

Because laser-cutting material removal operations often exhibit poor depth-control during cutting, the affiliated keep-out region, shown in Figure 5 (a), must be defined in such a way to prevent the laser from cutting in any region where the desired laminate ($\mathbf{L}$) exists. This is accomplished with the equation

$$\text{laserkeepout}\left(\mathbf{L}\right) = \left(L_i : i \in [\kappa]\right), \text{ where} \tag{37}$$

$$L_i = \bigcup_{L_j \in \mathbf{L}} L_j. \tag{38}$$

With different machining and material-handling processes comes the ability to access regions inaccessible by a laser. Since an end-mill's cutting volume is controllable in z, its keep-out region (Figure 5 b) can be calculated with the equation

$$\text{millkeepout}\left(\mathbf{L}\right) = \left(L_i : i \in [\kappa]\right), \text{where} \tag{39}$$

$$L_i = \bigcup_{j \in (i, i+1, \dots, \kappa)} L_j. \tag{40}$$

As the keep-out region defines the region of tool access, and as the convention of Equation (39) assumes tool access from above the part, a flipped laminate produces a different keep-out region. The keep-out region for $\mathbf{L}^f$ with a milling operation can be obtained by combining Equations (30) and (39), resulting in

$$\text{millkeepout}\left(\mathbf{L}^f\right) = \left(TL_i : i \in (\kappa, \kappa - 1, \dots, 1)\right), \text{where} \tag{41}$$

$$L_i = \bigcup_{j \in (i, i-1, \dots, 1)} L_j. \tag{42}$$

If the product of Equation (41) is itself flipped, the transform term T disappears, which, using Equation (36), allows us to merge the results of Equations (39) and (41). Any process that supports both milling and flipping will thus in general produce a smaller keep-out region, as seen in Figure 5 (c), with

$$\text{millflipkeepout}\left(\mathbf{L}\right) = \text{millkeepout}\left(\mathbf{L}\right) \cap^{\kappa} \text{millkeepout}\left(\mathbf{L}^f\right)^f. \tag{43}$$

It is important to note that while three keep-out functions have been defined here, it is possible to understand tool access for other types of machining and to develop complementary keep-out regions for each. In doing so, future material removal operations can be accommodated within the same framework with only an adjustment for the particulars of each operation. For generality we will use the term keepout($\mathbf{L}$) to describe the generation of a keep-out region of some laminate $\mathbf{L}$.

3.4.2. Preferred Cut Sequence While the non-contact aspect of bulk machining with a laser can reduce the forces seen on laminates, the manual (or robotic) parts of the process – material handling, alignment, and lamination – can impart relatively high stresses on semi-flexible layers and stretch the material, especially when a large amount of supporting geometry has been removed. The affected geometry tolerances can be a source of part flaws in subsequent placement and lamination steps. For this reason,

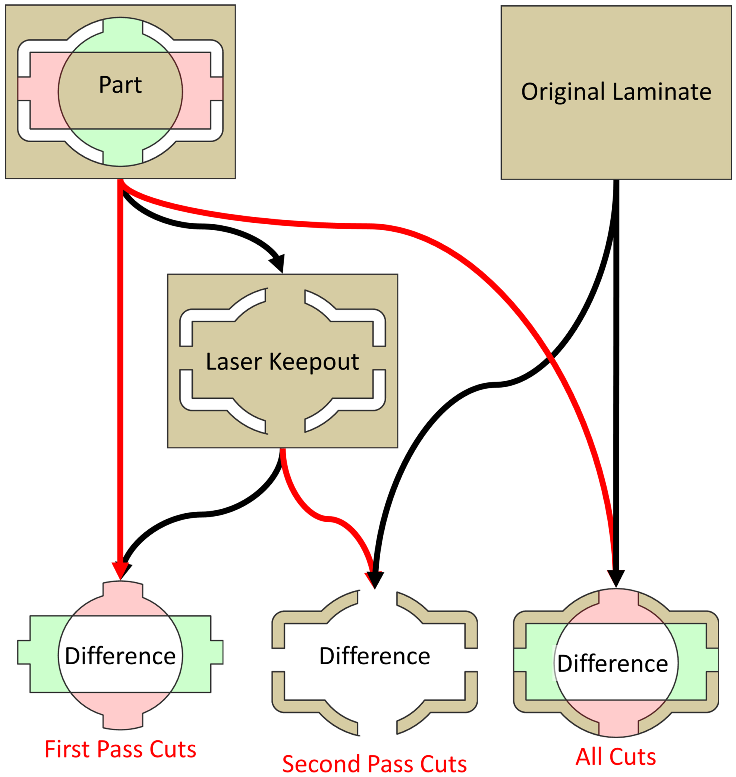

Figure 6. A keep-out region can help split cut geometries between cuts which must be performed prior to lamination, and those geometries which may be cut afterward. Black lines indicate addition, and red lines indicate subtraction.

it is often desirable to remove as little material as possible prior to lamination. If cut afterward, stiff structural layers can help support the softer ones during subsequent material handling and alignment stages and keep part dimensions more precise.

The concept of the keep-out region (Section 3.4.1) can help us determine which cuts can be offloaded to later stages. By manipulating the expression which defines the final geometry of the desired device we can sort cuts which must occur before lamination and those which can be performed after, based on the sets of points which are safe to cut prior to the lamination stage, as defined by the keep-out region.

Say $\mathbf{K}$ defines the keep-out region of some laminate. $\mathbf{C}$, some desired cut geometry, can be split into the components $\mathbf{C}^-$ and $\mathbf{C}^+$, where

$$\mathbf{C} = \mathbf{C}^- \cup^\kappa \mathbf{C}^+ \text{and} \tag{44}$$

$$\mathbf{0} \neq \mathbf{K} \cap^\kappa \mathbf{C}^-, \text{ and} \tag{45}$$

$$\mathbf{0} = \mathbf{K} \cap^\kappa \mathbf{C}^+. \tag{46}$$

$\mathbf{C}^+$, satisfies Equation (35), containing only geometry which can be cut subsequent to lamination. $\mathbf{C}^-$, however, cannot be cut after lamination because Equation (45) conflicts with Equation (35).

3.4.3. Theorem $\mathbf{C}^-$ can always be removed prior to lamination.

3.4.4. Example / Proof The equation $\mathbf{D} = \mathbf{L} \setminus^{\kappa} \mathbf{C}$ represents removing cut geometry $\mathbf{C}$ from laminate $\mathbf{L}$ to produce a laminate $\mathbf{D}$. As it is, however, removing $\mathbf{C}$ may not be possible with the available material removal process in the laminate if it conflicts with $\mathbf{D}$'s keep-out region $\mathbf{K}$, or in other words, if Equation (35) does not hold. To solve this problem, the cut laminate can be split between the geometry which can be cut before and after lamination, according to Equations (44-46), with

$$\mathbf{D} = \mathbf{L} \setminus^{\kappa} \left(\mathbf{C}^{-} \cup^{\kappa} \mathbf{C}^{+}\right). \tag{47}$$

Those points belonging to $\mathbf{C}^{-}$ can be applied prior to the lamination step. Prior to lamination, however, each layer of material may be considered a one-layer laminate itself, and can be promoted, resulting in

$$\begin{aligned}
\mathbf{D}_i &= D_i^1, &(48)\\
\mathbf{L}_i &= L_i^1, &(49)\\
\mathbf{C}_i^{-} &= \left(C_i^{-}\right)^1 &(50)\\
&\text{for } i \in [\kappa].
\end{aligned}$$

For such one-layer laminates $\mathbf{D}_i$, the three keep-out formulas 37, 39, and 41 each produce the same keep-out region $\mathbf{K}_i$, where

$$\mathbf{K}_i = \mathbf{D}_i. \tag{51}$$

With Equation (51) we can show that $\mathbf{C}_i^{-}$ is valid using Equation (35), where

$$\begin{aligned}
\mathbf{0} &= \mathbf{K}_i \cap^{\kappa} \mathbf{C}_i^{-}, &(52)\\
\mathbf{0} &= \mathbf{D}_i \cap^{\kappa} \mathbf{C}_i^{-}, &(53)\\
\varnothing &= \text{layer}\left(\mathbf{D}_i \cap^{\kappa} \mathbf{C}_i^{-}, 1\right), &(54)\\
\varnothing &= D_i \cap C_i, &(55)\\
\varnothing &= \left(L_i \setminus C_i\right) \cap \left(C_i\right), \text{ and} &(56)\\
\varnothing &= \varnothing &(57)\\
&\text{for } i \in [\kappa].
\end{aligned}$$

3.5. Lamination Process Considerations

3.5.1. Initial, Intermediate, and Final Cuts In addition to those cuts which must be front-loaded due to the restrictions of the machining process, alignment and identification cuts (Equations (27) and (28)) should be cut prior to the first lamination so they can be used for subsequent material handling operations. This allows us to define the initial cut $\mathbf{C}_0$ as

$$\mathbf{C}_0 = \mathbf{C}^{-} \cup^{\kappa} \mathbf{A} \cup^{\kappa} \mathbf{I}. \tag{58}$$

If a lamination process includes multiple lamination iterations, the secondary cut from the first lamination step can be merged with the initial cut from the second Figure 2, with

$$\mathbf{C}_j = \mathbf{C}^{+}_{j-1} \cup^{\kappa} \mathbf{C}^{-}_{j} \text{ for } j \in (1, \dots n), \tag{59}$$

where n is the number of lamination cycles. After lamination is complete, the release cut $\mathbf{C}^{-}_{n}$ may be applied to remove the device from the web at the regions where it is supported from the outside. Like all secondary cuts, however, this cut must stay out of the keep-out region defined by the final device laminate. The material contained within this cut laminate is often removed in an iterative fashion to allow for easier assembly of the pop-up device (as shown in Figure 2).

3.6. Dissassembly and Assembly Process Considerations

3.6.1. Z-Removability A closely-related topic to machinability is the concept of removability. Because cutting operations may produce scrap in addition to ablating material or creating chips, it is important to understand whether such scrap laminates can be easily removed. One easy measure of removability is whether scraps can be removed from above or below the planes of the laminates. We call this term z-removability, because it does not test the ability of scraps to move in the $\mathbb{R}^2$ space of the layer points, but in the $\mathbb{Z}^1$ space of the laminate. More general x-y-z-removability is related to the problem of assembly planning, and is not covered here.

Z-removability, however, is important in its own right because only one-dimensional operations are necessary with z-removable laminates, resulting in highly scalable manipulation and removal operations without intricate manual manipulation requirements; conceptually, removal could be automated using arrays of pushing or pulling tools all moving together.

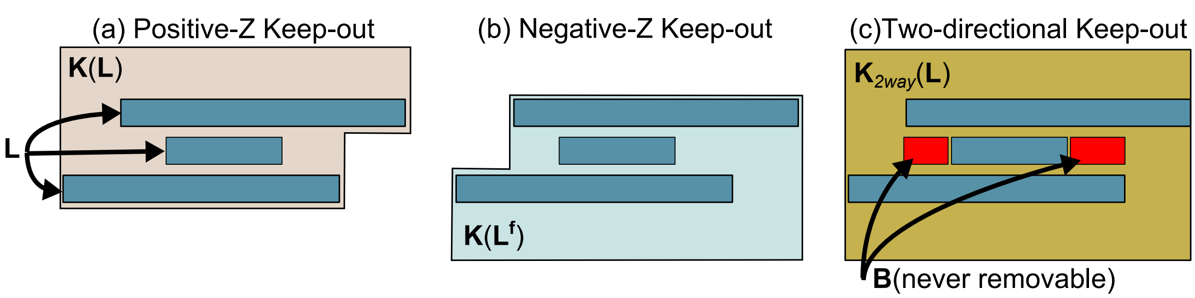

Figure 7. Three Removability Keep-Out Regions

Similarly to the machining keep-out region mentioned previously, a removability keep-out region can be defined to ensure z-removability in one or both directions. Any other laminate **A** may not occupy region **K** of laminate **L**, according to the expression

$$\mathbf{0} = \mathbf{A} \cap^{\kappa} \mathbf{K}(\mathbf{L}). \tag{60}$$

This region can be defined in a straightforward manner, as shown in Figure 7. Conceptually, as one laminate is removed from another, the geometries of the two laminates may not intersect through the removal path. As a laminate is removed in the positive z direction, its layer geometries pass by each layer above it. Therefore, for a laminate $\mathbf{L} = (L_1, \ldots, L_\kappa)$

$$\mathbf{K}(\mathbf{L}) = \left(L_i : L_i = \bigcup_{j \in (1,\ldots,i-1,i)} L_j \text{ for } i \in [\kappa] \right) \quad (61)$$

$\mathbf{L}$'s removability in the negative direction can be tested by finding a similar region for the flipped laminate $\mathbf{L}^f$. For $\mathbf{L}$ to be removable in both directions, $\mathbf{A}$ may intersect with neither $\mathbf{K}(\mathbf{L})$ nor $\mathbf{K}(\mathbf{L}^f)$. Combining Equations (60) and (61) for both $\mathbf{L}$ and $\mathbf{L}^f$ results in a new region $\mathbf{K}_{2way}(\mathbf{L})$, where

$$\mathbf{K}_{2way} = \mathbf{K}(\mathbf{L}) \cup^\kappa \mathbf{K}(\mathbf{L}^\mathbf{f}) \text{ and} \quad (62)$$

$$\mathbf{K}_{2way} = \left(\bigcup_{L_i \in \mathbf{L}} L_i \right)^\kappa . \quad (63)$$

As also seen in Figure 7, regions of material ($\mathbf{E}$) which are removable in neither z direction can be defined by the expression

$$\mathbf{E} = \mathbf{K}(\mathbf{L}) \cap^\kappa \mathbf{K}(\mathbf{L}^f) - \mathbf{L}. \quad (64)$$

In general, any material which exists in $\mathbf{E}$ should be cut from these regions prior to lamination to ensure their z-removability.

For laminates which are only one-way removable from their surroundings, it is often beneficial to give manufacturers the ability to both push and pull on the material. Unlike pulling, a process which usually involves using tweezers or small thin objects to get under and pry the laminate free, pushing operations can be quite simple and are more easily automated. For a laminate to be pushable, some hole $h \in \mathbb{R}^2$ must give the manufacturer access to the pushing face, where

$$\varnothing \neq h \cap \left(\bigcup_{L_i \in \mathbf{L}} L_i \right) \text{ and} \quad (65)$$

$$\varnothing = h \cap \left(\bigcup_{A_i \in \mathbf{A}} A_i \right), \quad (66)$$

for some surrounding laminate $\mathbf{A}$.

3.6.2. Separation and Disassembly of Support The web which surrounds laminate devices built using the PC-MEMS process is ideal for supporting and aligning the emergent device throughout the process. Other rapid prototyping systems – such as 3D Printing – also utilize support material which is often broken, dissolved, or melted

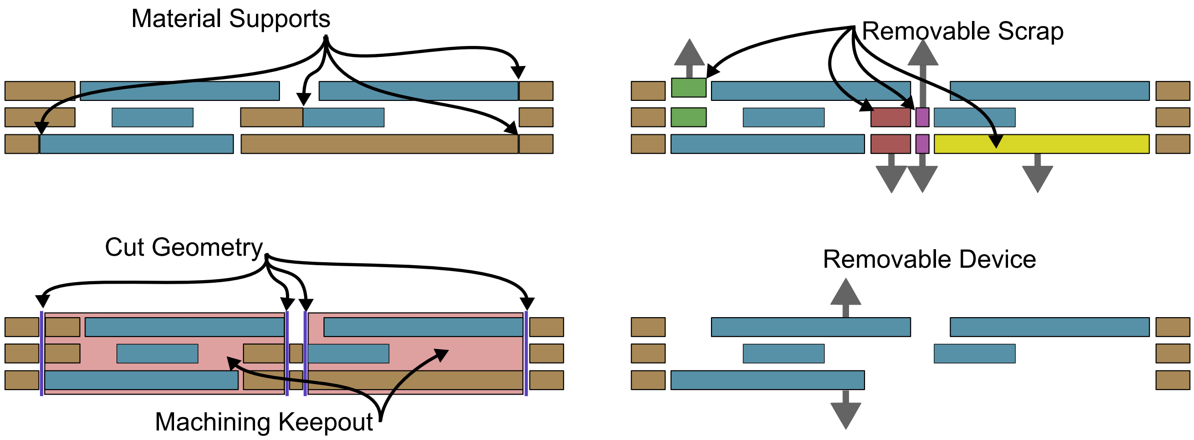

Figure 8. Four steps of support removal. The robot, in blue, is originally connected to the web, indicated in brown (top left). Cuts are performed(bottom left) outside of the device's keep-out region, freeing parts of the support (top right), allowing the newly removable scrap pieces to be disassembled. This leaves the device removable in both directions (bottom right).

away, but objects are generally supported in the z-direction. Unlike 3D Printing, the support material of a laminate device produced with PC-MEMS is the surrounding laminate, which, like other scrap, is affected by the constraints of the available material removal processes, and can only be placed in locations which are both machinable and/or removable after lamination.

The relationship between a support and device encompasses many of the previously-discussed concepts. Because the device and support come from the same material sheets, starting the process as a single, connected laminate, material removal operations must divide that laminate into separate connected pieces consisting of the device and one or more pieces of scrap. The device must be removable from those pieces, although some scrap may be removed first. The material removal step produces $\mathbf{L}_i$, where

$$\mathbf{L}_i = \mathbf{L}_{i-1} \setminus^{\kappa} \mathbf{C}_{i-1}, \text{ subject to} \tag{67}$$

$$\mathbf{0} = \mathbf{C}_{i-1} \cap^{\kappa} \text{keepout}(\mathbf{L}_{i-1}). \tag{68}$$

The resulting laminate should produce a mapping

$$\text{connected}(\mathbf{L}_i) = \mathbf{L}_{i1}, \ldots, \mathbf{L}_{im}, \text{ where} \tag{69}$$

$$m > 1, \tag{70}$$

and at least one connected laminate $\mathbf{L}_{ij} \in \mathbf{L}_i$ is removable, according to the concepts discussed in the last section. Removal of this piece can be described by

$$\mathbf{L}_{i+1} = \mathbf{L}_i \setminus^{\kappa} \mathbf{L}_{ij}. \tag{71}$$

This process, involving the repetition of Equations (67) and (71), can be repeated until the final device $\mathbf{D}$ exists in the collection of connected pieces produced by Equation (69), and is removable. A valid support is therefore any laminate which supports this iterative device-freeing process.

Once parts of the final device are released from their support, they can be assembled and locked into their final configurations to create the final device. This operation moves parts of the laminate into new positions, requiring a recalculation of the keep-out region with the now three-dimensional device. The new configuration of the device changes what scrap can be accessed at the next removal step, and can create new interference issues. In general, however, access to scrap and new cutting regions only grows as more parts become mobile, justifying only two-dimensional analysis as sufficient for guaranteeing manufacturability.

4. popupCAD: New Software

Several factors motivate the development of design software that directly supports the manufacturing paradigm outlined in Section 3. First and foremost is the desire to eliminate design errors resulting from users hand-checking their designs for manufacturing and assembly errors. Software which keeps track of the manufacturing rules can free the designer to focus on higher-level design elements. Because the geometry of each feature is currently often redrawn in two dimensions after the three-dimensional kinematic model has been developed, design errors can also result from omissions during that translation. Object-oriented principles could be applied to the modeling strategy, allowing for reuse of common features and reducing the chance of errors.

Another driving motivation for a new process is to reduce manufacturing errors due to manual assembly steps. The small size of mechanisms built with PC-MEMS technology is such that manual assembly operations are cumbersome, often requiring "surgeon's hands" and a microscope to attach small parts together. Assembly scaffolds have demonstrated the ease with which complex three-dimensional structures can be assembled with as few as one degree of freedom in the assembly step [33]. These structures simplify the assembly process by eliminating many manual folding, alignment and gluing operations, and have the potential to increase the yield of successful devices, in the spirit of Feynman's "hundred tiny hands" [12]. While such fixtures can facilitate precise assembly, their complexity has limited their use to a few special cases and a limited number of mechanisms. A more streamlined design process would reduce the complexity experienced by the user and permit more designs to take advantage of this powerful assembly concept. As noted in the introduction, the benefits of such an approach are shared with the VLSI design process and the MOSIS project, among others.

To spread PC-MEMS and printable robot technology into the larger community of researchers and designers, the design process must be just as accessible as the manufacturing tools. By streamlining the process and encapsulating manufacturing complexity, non-experts will be able to design better devices. With a common design platform and file specification, designs could be shared between designers or uploaded to a common web platform, building a community of designers able to contribute to this new technology.

4.1. Existing Design Process

The existing design process, which uses commercial 3D CAD software, can be summarized by the following steps:

Develop a three-dimensional CAD assembly of the desired robot. Any popup-compatible mechanism must be kinematically consistent with being able to be folded flat into a single laminated sheet. Not only must both the flattened and final configurations be free from part intersections, moving bodies must not interfere with each other as the parts in the flattened mechanism rotate into the final configuration.

Split the assembly into independent bodies. As each body of the mechanism is derived from the same original sheet, it must be assembled from an ordered subset of the same layers, each with their own geometric definitions and functional capabilities. This imposes requirements on joint locations, for example, as each joint must be located on layers which can support hinging. It also imposes restrictions on individual part thicknesses, as each part of the same layer must be the same height.

Create feature geometry. Complex features are often found in pop-up devices. These may be something like a castellated joint [33], where the requirements for an accurate hinge location and small bend radius require special geometry on many part layers. Feature complexity may also arise out of the need to reroute conflicting joint locations between or within layers.

Flatten the assembly and generate manufacturable two-dimensional layer drawings. Each layer of the laminate must be drawn from the edges of the individual parts which comprise it. Special care must also be taken that individual features, such as castellated hinges, do not contain lines which intersect with other necessary parts or features. Manufacturability issues may also arise if the laser is unable to reach a required cut on an inner layer. Conflicting features must be repaired in the three-dimensional assembly and layer drawings re-extracted and re-inspected. This is generally an iterative process where many errors must be found and fixed, and also the step of the process which could benefit most from a manufacturing-specific approach.

Build the device. This is a necessary part of the design process, as design errors may be overlooked in previous steps, especially by inexperienced designers unfamiliar with the manufacturing rules.

4.2. Re-envisioning the process through the use of manufacturing-aware software

A new design suite called popupCAD has been implemented in Python and QT which implements the analytical framework outlined in Section 3. At the core of popupCAD is the ability to create and perform operations on two-dimensional geometric

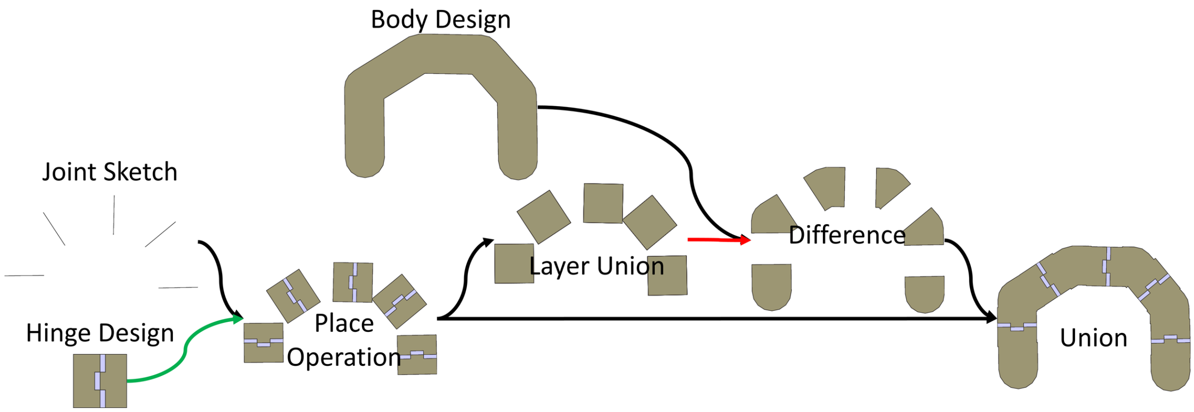

Figure 9. The popupCAD design process. Additive geometry is represented by black arrows, subtractive by red.

primitives. The operations available to the user are the same basic operations available in the analysis framework. Addition, removal, union, intersection, difference, dilate, and erode form the basic operations available at both the layer and laminate level. Currently, popupCAD supports lines, polylines, circles, and polygons. These polygons can be created from an original sketch composed in popupCAD or by exporting body information from Solidworks. Once these two-dimensional primitives are defined, they can be operated upon in a variety of ways in order to define the bodies and joints of the final robot, as well as the support material, original sheet geometry, and anything else necessary to capturing the manufacturing process.

Design operations are added sequentially in an operation list, which maintains an accounting of each operation applied and the geometry that results. While the list itself is sequential, each operation may refer to the results of one or more prior operations. This results in an acyclic network of connected operations both hierarchical and directed in nature, as seen in Figure 9. An operation may depend on a number of previous operations, and generates geometry which can be reused by any subsequent operation in the operation list.

4.3. Proposed Design Process: Developing a manufacturable device with popupCAD

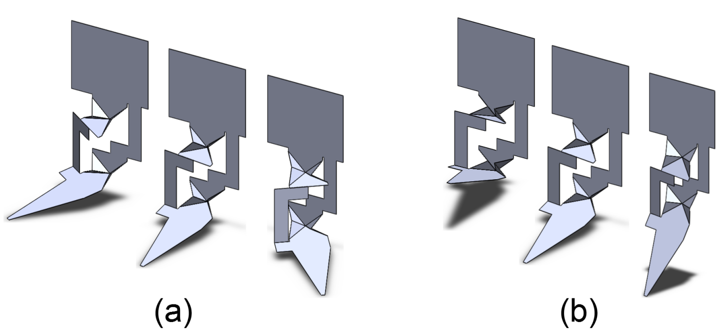

Figure 10. A new leg design featuring (a) swing and (b) lift degrees of freedom.

Developing a manufacturable PC-MEMS-enabled device begins by sketching the device in its flattened state. Figure 10, for example, shows a design for a two degree-of-freedom leg capable of lift and swing motion via coupled spherical joints created from two six-bar linkages. This model, developed in Solidworks, can be exported into a format which can be read by popupCAD. This is especially useful because the three-dimensional environment of Solidworks provides a high level of understanding regarding the kinematics of the emergent device, as yet unavailable in popupCAD.

Designing the device directly in popupCAD can also be accomplished in only a few steps, as outlined in Figure 9. First, the desired material making up the body of the device is created. The outline of the device is generally sufficient to get started, as it can be subsequently split into individual bodies. Adhesive geometry can often be generated from the intersection of the layer's neighbor geometry; a cleanup sketch is all that is required to remove remaining unwanted areas of adhesive. Figure 11 (a) shows an equivalent design drawn directly in popupCAD

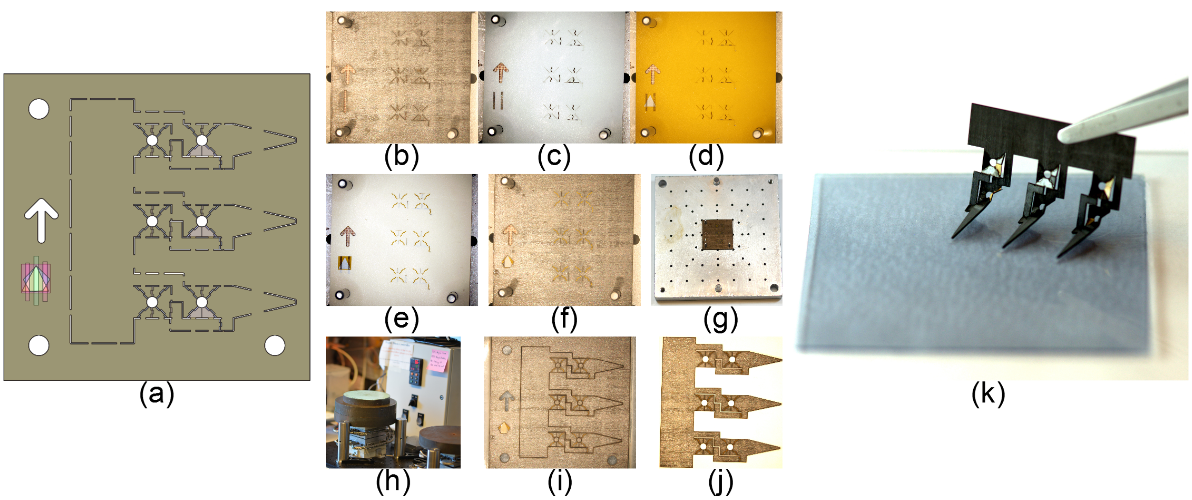

Figure 11. Leg Fabrication Process. (a) a design for a 2-DOF leg in popupCAD, (b-f) cutting and stacking of individual layers, (g) layers prepared for lamination, (h) lamination, (i) after cutting, (j) after release, (k) after popup.

Joint material can be added in a more efficient way, allowing existing joint designs to be merged with the new body geometry. This is accomplished using a sketch containing simple lines. These lines serve several purposes in the placement of joints. First, they define the kinematics of the final device; their geometry defines how the parts of the emergent device will move. Second, they can be dilated and used as material removal tools to split the device body into individual parts and create space for placing the eventual hinge design. And third, they position the new joint material through a material placement operation, as seen in Figure 9. Once the joint lines are specified, the material surrounding the new joints is removed, and joint material is placed to facilitate the type of motion desired for the individual joint. This is one example of where an object-oriented design structure can be quite beneficial, as a single joint design can be reused multiple times across many devices and joints. Placement of the hinge material is automated in popupCAD by a matching a line from the hinge design to the line sketch of joint locations. Joint material and body material are then merged by unioning the two laminates together, creating the device design.

Because the operations in popupCAD encapsulate the framework outlined in Section 3, it is possible to split cuts, create machining keep-out regions, design removable supports structures, and determine material removal steps for the new device. A series of cut files can be produced which generate the necessary cut geometries required to produce the device. Figure 11 shows the manufacturing steps and final result for the two degree-of-freedom leg of Figure 10, produced entirely in popupCAD.

5. Conclusions and Future Work

A more direct method for developing and analyzing functional laminate structures has been proposed, and is being implemented in the form of a suite of design and manufacturing tools called popupCAD. Several opportunities for this tool have been identified: first, to speed up work-flow by allowing designers to design laminate mechanisms directly defining features and operations common to the manufacturing paradigm; second, to reduce the number of manufacturing iterations by providing design-time intuition about kinematics, dynamics, and manufacturability; third, to enable faster development of higher-complexity devices by simplifying and streamlining the design process; and fourth, to enable people unfamiliar with the details of the manufacturing process develop sophisticated devices from common, shared, design elements.

Future work will seek to utilize the framework introduced here towards the development of process-specific algorithms which can be used for automatically generating support structures, cut files, and manufacturing process plans. The authors also envision using popupCAD for analyzing higher-level manufacturing issues, such as those imposed by non-zero kerfs, thick layers, and the limitations of other material removal processes. With the knowledge of material properties and material distribution, popupCAD will also be uniquely poised to give designers knowledge of the emergent device's kinematic and dynamic properties, for identifying assembly issues during manufacturing and understanding motion once released.

Acknowledgments

This material is based upon work supported by the National Science Foundation (grant numbers EFRI-1240383 and CCF-1138967) and the Wyss Institute for Biologically Inspired Engineering. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

The authors would like to thank Alex Cornejo for his assistance in formulating and wording the mathematical sections.

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