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DRAFT: ALGORITHMS FOR RAPID DEVELOPMENT OF INHERENTLY-MANUFACTURABLE LAMINATE DEVICES

Daniel M. Aukes*
Robert J. Wood
Wyss Institute for Biologically Inspired Engineering,
School of Engineering and Applied Sciences,
Harvard University, Cambridge, MA 02138

ABSTRACT

We present several algorithms suited for the generation and analysis of structures used in manufacturing laminate electromechanical devices. These devices may be fabricated by a family of related manufacturing processes such as printed-circuit MEMS (PC-MEMS) smart composite microstructures (SCM), or lamina emergent mechanisms (LEM), which, by utilizing multi-material laminate composites, enables kinematic motion, component embedding, and monolithic fabrication of high-precision millimeter-scale features. The presented algorithms enable rapid generation of manufacturing features such as support structures and cut files, while facilitating integration with the user's design intent and available material removal processes. An exemplar device is presented, which, though simple in concept, could not be manufactured without the aid of an expert designer to produce the same features generated by these algorithms.

1 INTRODUCTION

Recent work in micro-robotics has demonstrated the utility of millimeter-scale robotic devices which utilize layered manufacturing techniques such as PC-MEMS to create complex, multi-jointed devices capable of a high degree of precision. The utilization of layered manufacturing techniques drives this precision, enabling the placement of mechanical components such as joints, links, springs, and actuators through selective material removal in a multi-material laminate. The use of popup-book assembly processes can further reduce common manufacturing flaws by reducing the number of manual assembly steps, which at this scale must often be done under a microscope by an expert.

The workflow of designing the manufacturing process for such laminate devices, however, is less automated than with more common processes such as milling. At this time, existing commercial CAD/CAM software does not address all the needs of this new manufacturing process, requiring designers to internalize many of the manufacturing rules associated with PC-MEMS. This results in a cumbersome design process which relies on an expert designer to find and eliminate design errors. The dependence on a variety of software packages further slows the design process, since the designer must often restart the design process at the beginning when fundamental errors in the design are found.

In this paper we present several algorithms which facilitate rapid development of inherently-manufacturable laminate devices. These algorithms are based on an analytic framework of laminates which facilitates the geometric analysis of laminates, while factoring in the constraints of available manufacturing processes. Using these techniques we can show that many aspects of laminate manufacturing can be automated, including determining machine tool access, generating support structures, removing scrap, and assembling or erecting the device. In addition, we discuss ways to combine the users design intent with auto-generated manufacturing output, especially in cases where algorithms fail due to conflicts between the device design and process limitations.

Finally, we demonstrate the utility of such algorithms through the design of a single degree-of-freedom robotic mecha-

*Corresponding author

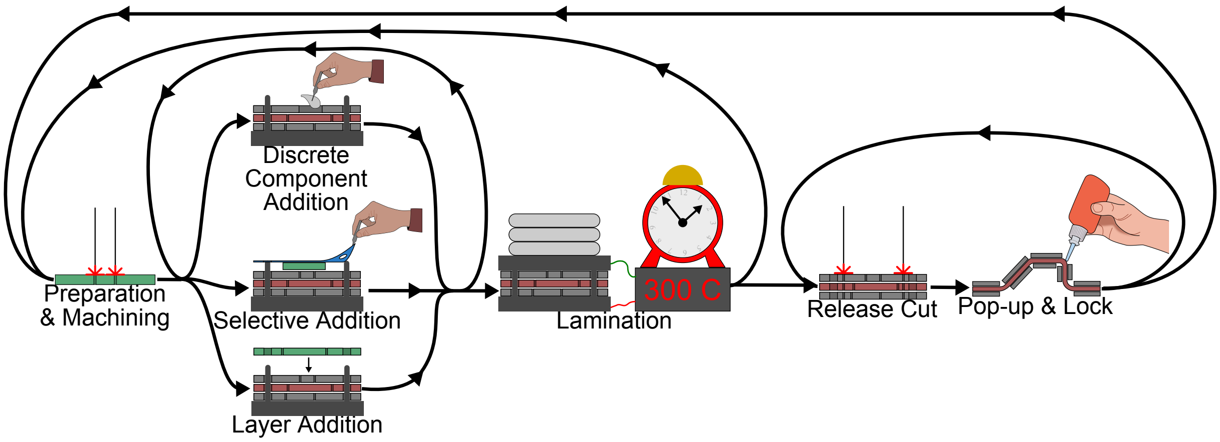


FIGURE 1. The general laminate manufacturing process outlined in [1].

nism, developed in new laminate design software we call popupCAD. Using object-oriented design principles alongside the analytic framework and manufacturing algorithms described above, we can demonstrate a streamlined design process which, using the current design workflow, would take considerably more time, for even low-complexity devices. This savings is realized by reducing manual drawing steps, automating the generation of features previously hand-drawn, and by lessening the dependence on manufacturing expertise to minimize design errors.

2 BACKGROUND

A variety of fabrication techniques related to laminte mechanisms have been introduced in the past decade [2–4]. The kinematics of pop-up books have been studied [5] and integrated with these fabrication techniques [6], resulting in devices which can achieve high precision due to persistent alignment features reused throughout manufacturing. This has led to advances in assembly techniques, where complex devices are assembled and locked into their final shape using single-degree-of-freedom scaffolds to replace manual placement and wave soldering to replace gluing steps [7]. These advances have made it possible to achieve repeatable, precise assembly of millimeter-scale electromechanical devices. The design process, however, relies on design tools not well suited to the manufacturing process. Despite its possibilities, the Mobee [7] remains one of only a few examples (along with [8]) of a device compatible with monolothic fabrication techniques due to the complexity of the design. Figure 1 summarizes the manufacturing process, outlined in greater detail in [1].

To faciltate the design of these layered devices, we have recently proposed a mathematical framework for such devices [1]. A result of this framework is popupCAD, a new design tool which allows users to create and operate on geometries which define material placement and cut geometry for two-dimensional laminate devices. Geometries are characterized by sets of two-dimensional planar geometries such as polygons, circles, and polylines distributed on each layer of material in the laminate. Simple operations combine one or more existing sets of geometries using common constructive solid geometry operations or define new laminate geometries based on user-drawn sketches or imported geometries. Other operations may perform very specific geometric operations between or within layer geometries of a number of laminates. As the output of an operation is also itself a laminate, this permits the user to chain many of these basic operations together into complex geometric operations which can be used to analyze the structure and thus the validity of a variety of components which assist in the manufacturing of laminate devices. It is with this tool that we imagine the creation of higher-level manufacturability tests and geometry generation procedures which can reduce the complexity of the manufacturing process plan, and enable users to speed their design workflow.

Validation and process planning for mature manufacturing methods such as machining, sheet metal folding, and stamping have been reviewed and studied in detail [9–11], and as a result, a variety of commercial computer aided machining (CAM) packages are available for such processes and more. In the field of layered manufacturing for example, a variety of algorithms and methods related to the determination of optimal part orientation, support structure, object slicing and deposition path planning are reviewed in [12]. For 3D printing, the most common implementation of layered manufacturing, this has resulted in a variety of proprietary software systems which automate these planning functions while providing decision support to the user to select the appropriate blend of build parameters based on the tradeoffs between precision, speed, time, and material use. This software is commonly bundled with 3D printers, making the transition from three-dimensional design to printed part rather seamless to the end user. Likewise, for shape deposition manufacturing, the iterative deposition and removal of material imposes specific sequence limitations and geometric constraints for embedded components, sacrificial support material, and device geometry; only through research in process planning [13–15] has the fabrication of multi-material devices with embedded discrete components become possible [16–18].

3 ALGORITHM FRAMEWORK[1]

3.1 MATHEMATICAL OPERATIONS

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

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

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

$$\mathbf{A} \cup^\kappa \mathbf{B} = (A_i \cup B_i)_{i \in [\kappa]} \tag{8}$$
$$\mathbf{A} \cap^\kappa \mathbf{B} = (A_i \cap B_i)_{i \in [\kappa]} \tag{9}$$
$$\mathbf{A} \setminus^\kappa \mathbf{B} = (A_i \setminus B_i)_{i \in [\kappa]} \tag{10}$$
$$\mathbf{A} \oplus^\kappa \mathbf{B} = (A_i \oplus B_i)_{i \in [\kappa]} \tag{11}$$
$$\mathbf{A} \ominus^\kappa \mathbf{B} = (A_i \ominus B_i)_{i \in [\kappa]}, \text{ where} \tag{12}$$
$$[\kappa] = (1, \dots, \kappa). \tag{13}$$

[1]The material in Sections 3.1-3.2 is summarized from [1]

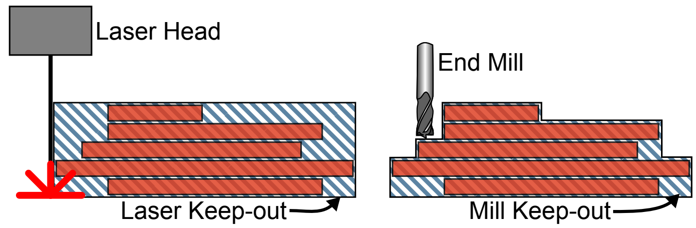


FIGURE 2. Two machining keep-out regions. A device(solid red) produces different keep-out regions(patterned blue) for laser cutting and machining.

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 as $\varnothing^\kappa$. Finally, individual layers of a laminate can be selected with the *layer*() mapping, where for some for some $A_i \in \mathbf{A}$,

$$A_i = layer(\mathbf{A}, i). \tag{15}$$

3.2 KEEP-OUT REGION

An important aspect of material removal is that each type of removal process has a different set of geometric constraints attached to it; this constraint is determined from the physical means by which material is removed. An end mill spins as it travels through space, cutting a volume which is determined both by the mill's dimensions and its path during a machining operation. An end mill's orientation is usually fixed with relation to the part, however, meaning that unless the part is re-fixtured, the tool can only approach the material from one direction. A laser, similarly, creates a similar cut volume determined by the width of the beam (kerf) and its two-dimensional path during a laser machining operation. The depth and angle of the cut, however, are usually determined by the laser's focus and cut parameters, rather than any travel in the cut head. Additionally, lasers often have poor depth control when cutting through thin or easy-to-cut materials. Other material removal processes have similar limitations which impact tool access, from photolithography and chemical etching to electrical discharge machining (EDM). To deal with these issues, we have proposed the concept of the machining keep-out region in [1], which can be used to define the material regions which must be preserved during specific material removal operations. Three such regions are introduced for laser machining, milling, and milling combined with part flipping. These three keep-out regions ($\mathbf{K}_l, \mathbf{K}_m, \mathbf{K}_{mf}$, respectively)

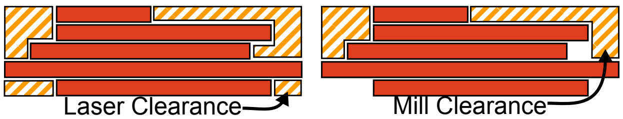


FIGURE 3. The tool clearance of a laminate is shown for both laser machining and milling operations. To reach the device(solid red), the material in the clearance region(patterned orange) will be affected.

for a laminate $\mathbf{L}$ can be defined as

$$\mathbf{K}_l(\mathbf{L}) = (L_i : i \in [\kappa]), \text{ where} \tag{16}$$
$$L_i = \bigcup_{L_j \in \mathbf{L}} L_j. \tag{17}$$
$$\mathbf{K}_m(\mathbf{L}) = (L_i : i \in [\kappa]), \text{where} \tag{18}$$
$$L_i = \bigcup_{j \in (i, i+1, \ldots, \kappa)} L_j. \tag{19}$$
$$\mathbf{K}_{mf}\left(\mathbf{L}^f\right) = (TL_i : i \in (\kappa, \kappa-1, \ldots, 1)), \text{where} \tag{20}$$
$$L_i = \bigcup_{j \in (i, i-1, \ldots, 1)} L_j. \tag{21}$$

In the rest of the text, $\mathbf{K}(\mathbf{L})$ will refer in general to a machining keep-out region, and a laser keep-out region will be used for all figures unless otherwise stated.

3.3 CLEARANCE

Procedure 1 Clearance Generation

> **procedure** CLEARANCE($\mathbf{L}$, *method*)
>   **if** $method = laser$ **then**
> $\mathbf{C} \leftarrow \mathbf{K}_l(\mathbf{L}) \setminus^\kappa \mathbf{L}$
>   **else if** $method = milling$ **then**
> $\mathbf{C} \leftarrow \mathbf{K}_l(\mathbf{L}) \setminus^\kappa \mathbf{K}_m(\mathbf{L})$
>   **end if**
>   **return C**
> **end procedure**

The keep-out region can be used to understand which geometry will be affected by a tool reaching a laminate $\mathbf{L}$. We call this the clearance region, and it is determined by Procedure 1. The clearance region of a laminate $\mathbf{L}_1$, for example, can be used to determine whether another laminate $\mathbf{L}_2$ is obstructing tool access according to the equation

$$\varnothing^\kappa = \text{CLEARANCE}(\mathbf{L}_1) \cap^\kappa \mathbf{L}_2. \tag{22}$$

If Equation (22) holds, $\mathbf{L}_2$ is not obstructing $\mathbf{L}_2$. The clearance of a laminate $\mathbf{L}_1$ can also be used to modify $\mathbf{L}_2$ so that it is guaranteed not to be in the access path of a tool or some other manufacturing step that uses keep-outs.

$$\mathbf{L}_2^* = \mathbf{L}_2 \setminus^\kappa \text{CLEARANCE}(\mathbf{L}_1) \tag{23}$$

4 ALGORITHMS

Designing material support is necessary for PC-MEMS devices because each layer of the laminate starts as an individual, continuous sheet of material. In the current manufacturing paradigm, the material which will end up in the device must be securely held during manufacturing to prevent alignment problems. This can be done by keeping material connected to the surrounding scrap which will later be removed, until after the lamination process has established layer alignment and bonding to neighbor layers has been completed. The design of such support structures is discussed in this section. A related consideration – the generation of allowable cuts – is discussed at the end.

4.1 WEB GENERATION

Procedure 2 Web Generation Method

> **procedure** WEB($\mathbf{L}, a, b, method$)
> $A \leftarrow layer(\mathbf{K}_{method}(\mathbf{L}), 1)$
> $B \leftarrow A \oplus$ (a circle of radius a)
> $C \leftarrow B \oplus$ (a circle of radius b)
> $D \leftarrow$ (a minimum-bounding-rectangle of C)
> $\mathbf{W} \leftarrow (D \setminus B)^\kappa$
>   **return W**
> **end procedure**

Web is scrap material which surrounds the final device, and is primarily used during the fabrication process to support device material prior to lamination. Web is eventually separated from the device by material removal operations to free the device near the end of fabrication. When designing a manufacturing process plan, it is important to identify how the device material will be held; the creation of web geometry is often the first step of designing such supports. It is often useful to keep a gap between device material and web material to ensure easier removal of the device once it is freed. The dilate operation (11) serves this purpose well. The following procedure generates such a web, as seen in Figure 4.

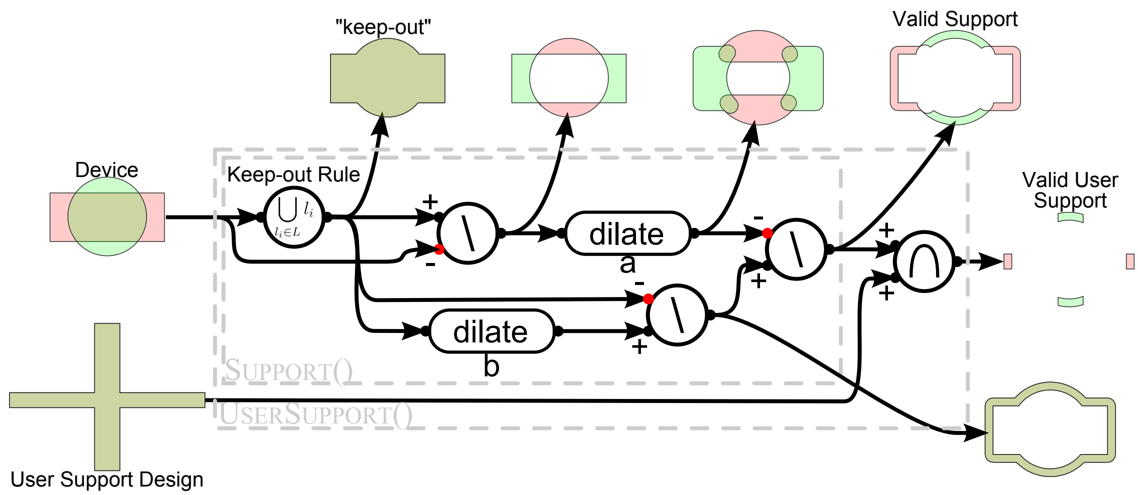


FIGURE 5. Support generation (Procedure 3) is outlined for a two-layer laminate device.

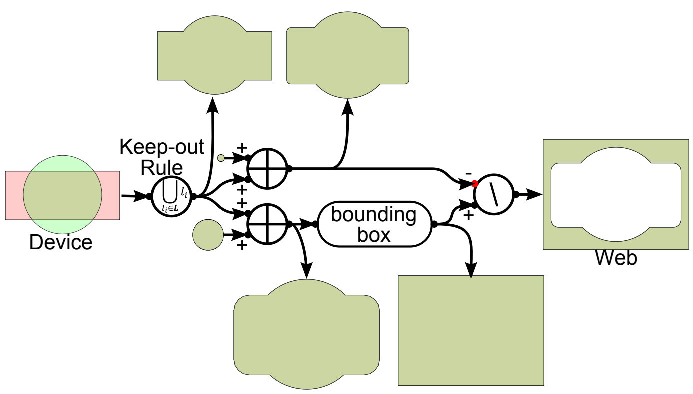


FIGURE 4. Web generation (Procedure 2). In this figure, green areas indicate one layer, red indicates another layer, and the combined green and red color indicates where material exists on both layers.

Procedure 3 Two Support Generation Methods

procedure SUPPORT($\mathbf{L}, a, b, method$)
    $\mathbf{A} \leftarrow \mathbf{K}_{method}(\mathbf{L})$
    $\mathbf{B} \leftarrow \mathbf{A} \setminus^{\kappa} \mathbf{L}.$
    $\mathbf{C} \leftarrow \mathbf{B} \oplus^{\kappa}$ (a circle of radius $a)^{\kappa}$
    $\mathbf{D} \leftarrow \mathbf{A} \oplus^{\kappa}$ (a circle of radius $b)^{\kappa}$
    $\mathbf{E} \leftarrow \mathbf{D} \setminus^{\kappa} \mathbf{A}$
    $\mathbf{S} \leftarrow \mathbf{E} \setminus^{\kappa} \mathbf{C}$
    return S
end procedure
procedure MERGESUPPORT($\mathbf{L}, \mathbf{U}, a, b, method$)
    $\mathbf{A} \leftarrow$SUPPORT(($\mathbf{L}, a, b, method$))
    $\mathbf{S} \leftarrow \mathbf{S} \cap^{\kappa} \mathbf{U}$
    return S
end procedure

4.2 SUPPORT GENERATION

One important design guideline is that any material used to support individual layers must removable after lamination. Material support which is designed by the user must be checked for this property, and that which is generated must be done according to that rule. As the machining keep-out region can be used to determine tool accessibility for a given geometry, it can be used in conjunction with the post-lamination geometry to identify regions which will be valid candidates for adding supports. Figure 5 highlights the following process outlined in Procedure 3.

Because designers are often driven by other requirements, and may want support regions in only certain places, there must be a way to merge valid support regions with the users intent. **S** is generated by intersecting two laminates: a valid support laminate, **F**, and a user-supplied support laminate, **U**. This restricts valid support material to the region within the user-supplied geometry.

4.2.1 Validity Check

Depending on the user design and material removal method, the support generation method cannot always generate a valid support design. This can be shown with a simple counter-example, shown in Figure 6. Because of the limitations of material removal processes such as laser machining, some material layers may become obscured by others, preventing any support – which must be removable after lamination – to secure the device. Support designs can be checked for validity by performing a union operation on the web, device, and support, and checking each layer for multiple individual shapes per layer. The existence of more than one indicates that some unsupported island of material is not connected to the surrounding web and cannot be supported prior to lamination. This requires one of two things: **(1)** a new material removal

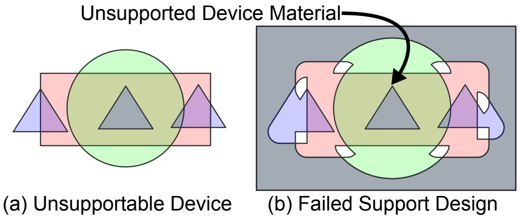


FIGURE 6. Given the assumption of laser machining, the three-layer (red,green,blue) device design in (a) cannot be supported because the circle and square completely obscure the center triangle. In contrast, the left and right triangles, partially unobscured, can be supported. In (b), the generated support and web designs are unioned to the device, leaving the center triangle unconnected to the web, and the outer triangles merged with the surrounding support.

method must be selected which has better tool access, or **(2)** the device design must be changed in a way which gives these islands access to the support.

4.3 DEVICE MODIFICATION

Procedure 4 Device Modification Method

procedure $\text{MODIFYDEVICE}(\mathbf{L}, \mathbf{U}, a, b, c, method)$
- $\mathbf{A} \leftarrow \mathbf{L} \oplus^{\kappa}$ (circle of radius $a)^{\kappa}$
- $\mathbf{B} \leftarrow \mathbf{A} \setminus^{\kappa} \mathbf{L}$
- $\mathbf{S} \leftarrow \mathbf{U} \oplus^{\kappa}$ (circle of radius $b)^{\kappa}$
- $\mathbf{C} \leftarrow \mathbf{B} \cap^{\kappa} \mathbf{S}$
- $\mathbf{D} \leftarrow \text{CLEARANCE}(\mathbf{C}, method)$
- $\mathbf{E} \leftarrow \mathbf{D} \oplus^{\kappa}$ (circle of radius $c)^{\kappa}$
- $\mathbf{L}^* \leftarrow \mathbf{L} \setminus^{\kappa} \mathbf{E}$
- **return** $\mathbf{L}^*, \mathbf{S}$

end procedure

Because auto-support generation is not guaranteed to succeed, and because it is not always convenient or possible to switch material removal methods, there must be a mechanism for allowing users to modify their device designs in a way which makes it supportable. This is accomplished with Procedure 4, as seen in Figure 7. Instead of finding all regions from which valid supports can be drawn, as in Procedure 3, this procedure takes a line drawing input by the user which indicates where supports shall be placed, and creates holes in the laminate device which allow supports both to hold on to selected layers, and to be removable after lamination.

In order to create valid support design for an entire device, a non-expert designer can utilize a mix of support generation and device modification in order to make a manufacturable device. Expert designers may always be able to design supportable parts, but the average user may not understand what geometries enable a design to pass the support check (Section 4.2.1). The device modification procedure allows the user to quickly modify the device in a way which does not alter unintended geometries, without having to start over from scratch and rethink a design. Procedure 4 will enable a much larger user base to take an initial non-manufacturable design and make it manufacturable.

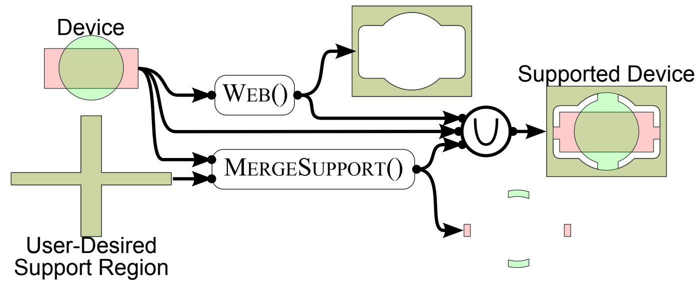


FIGURE 8. A two-layer supported device, with generated web and supports.

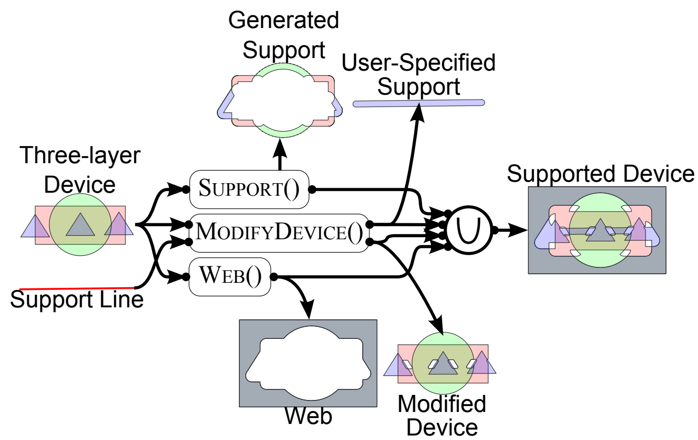


FIGURE 9. A three-layer initially unsupportable device, modified, with web and supports generated.

4.4 MERGING SUPPORTS

Figures 8 and 9 show several ways of combining the previous procedures depending on user preferences and the state of the laminate device design. If it is initially supportable, the user may wish to autogenerate all support, and supply a suggestion for where he or she would prefer support to be placed, as in Figure 8. If the device is more complicated as discussed in Section 4.2.1, the user may need to modify the device and merge that design with the generated support and web designs. This allows for the highest level of flexibility, as the user can be relied upon to modify the device in a way which will not alter the function, yet takes advantage of the automation provided by support and web generation.

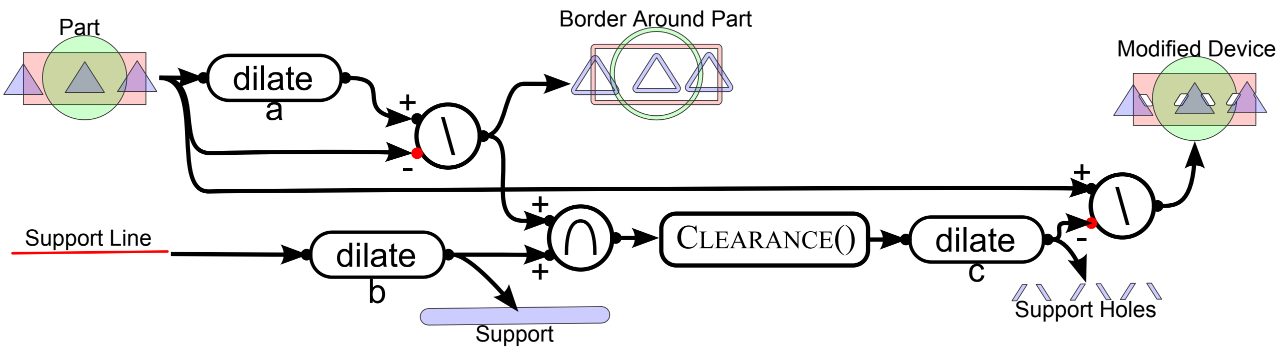


FIGURE 7. Device modification (Procedure 4) is outlined for a three-layer, inintially-unsupportable laminate.

4.5 MATERIAL REMOVAL ORDER: CUT SPLITTING

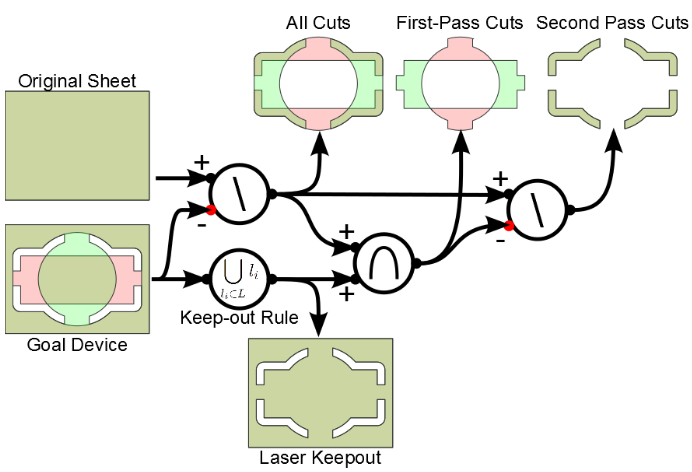


FIGURE 10. The cut splitting process (Procedure 5) is shown. This process uses the keep-out rule for a partcular material-removal process to filter scrap geometry between that which can be accessed prior to lamination, and that which can be accessed afterwards.

Procedure 5 Cut Splitting Method

procedure SPLITCUTS($\mathbf{L}, \mathbf{S}, method$)
  $\mathbf{A} \leftarrow \mathbf{K}_{method}(\mathbf{L})$
  $\mathbf{B} \leftarrow \mathbf{S} \setminus^{\kappa} \mathbf{A}$
  $\mathbf{C}_1 \leftarrow \mathbf{A} \cap^{\kappa} \mathbf{B}$
  $\mathbf{C}_2 \leftarrow \mathbf{B} \setminus^{\kappa} \mathbf{C}_1$
  return $\mathbf{C}_1, \mathbf{C}_2$
end procedure

Currently, users must hand-design their own cut files from two-dimensional sketches of each layer, painstakingly adding or removing individual cut lines as they determine whether each can be cut at a particular step in the process. This results in designers creating simpler robots to facilitate easier generation of cut files. When impossible, the process is slow and errors are many, both in the design and prototyping stage, requiring many more prototype iterations to work out the design flaws.

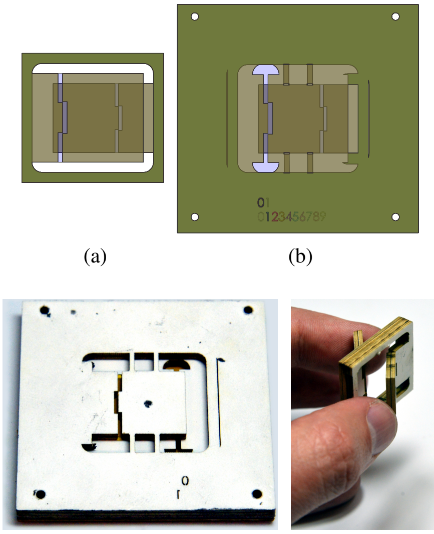
Procedure 5 allows one to determine which material must be removed before that material becomes inaccessible to the selected material removal process. All other geometry may be removed after lamination. The machining keep-out region is used in this case to sort geometry in preparation for material removal processes.

5 MOTIVATING EXAMPLE

Often, even simple designs have rather complicated manufacturing considerations, due to the limitations of both the design and the available material removal process. Figure 11a shows one such device consisting of eleven layers, with hinged elements which overlap each other. Due to one of the hinge elements obscuring the other, this design would either need to be laminated in several steps or modified by an expert designer with knowledge of the access limitations of the laser. Using the process outlined in Figure 9, however, the device is easily modified by adding access holes to the device which facilitates support removal, producing the supported device design in Figure 11b. The actual device developed by this process is shown in Figure 11c prior to the final cut, and in Figure 11d after release.

6 FUTURE WORK AND CONCLUSIONS

These algorithms have been experimentally determined and validated using the manufacturing processes found in our lab. While they seem work for our own processes, little work has been done to verify their generality across the family of manufacturing paradigms used to make SCM and LEM devices. Future work will generalize across these paradigms to encompass a variety of process constraints not yet anticipated, while continuing to allow



(a) (b) (c) (d)

FIGURE 11. Example Device (a) popupCAD design, (b) supported popupCAD design, (c) supported by the web, prior to the release cut, and (d) after release, in its deployed state.

for specificity within each paradigm.

In addition, the algorithms here represent only a small portion of those needed to ensure a generally-manufacturable laminate device. We hope to expand our analytic capabilities to other aspects of manufacturing, such as device freeing, assembly, and locking steps. Finally, as many design and manufacturing decisions come with inherent trade-offs which can affect build time, cost, and material use, we hope to investigate the potential for optimization across the set of manufacturing parameters. Just as with 3D printers, we hope that some day the algorithms here form the foundation for a suite of tools which makes laminate device manufacturing a fully-automated process which can be tailored to each manufacturing line, or perhaps even to a single PC-MEMS machine.

ACKNOWLEDGMENT

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