Joinery: Parametric Joint Generation for Laser Cut Assemblies

Clement Zheng[*†] **Ellen Yi-Luen Do**[*] **Jim Budd**[*]

[*] Georgia Institute of Technology [†] National University of Singapore

clement.zheng@gatech.edu ellendo@gatech.edu jim.budd@design.gatech.edu

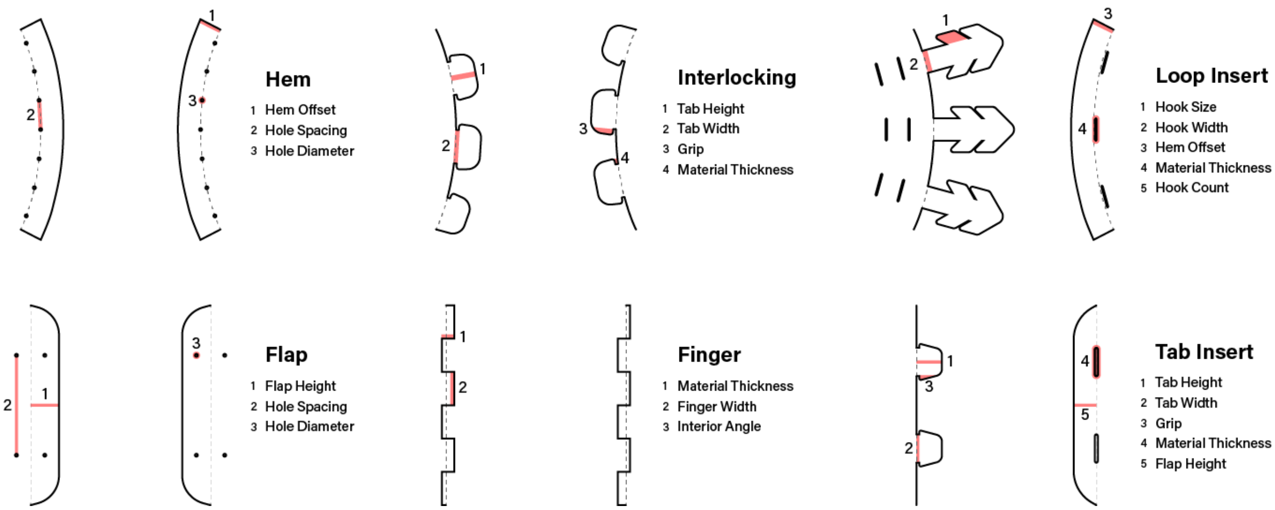

Figure 1: Joinery's parametric joint profiles for laser cutting.

ABSTRACT

Laser cutting is widely used by industrial designers and mechanical engineers as a rapid modeling tool. However, designing and fabricating laser cut assemblies can be a complex and tedious process, especially for novice designers. Through our research, we developed *Joinery*, a parametric joint generation tool for laser cut assemblies. Through *Joinery*, designers simply define connections between parts of an assembly, while the system generates the joints. *Joinery* supports fabrication-aware design through six different joint profiles that cater to different material and design needs. In this paper, we illustrate the use of *Joinery* as a creativity support tool in an industrial design process, and present several artifacts resulting from the tool. In addition, we discuss our findings from deploying this system in a college-level industrial design class.

C&C '17, June 27-30, 2017, Singapore, Singapore

DOI: http://dx.doi.org/10.1145/3059454.3059459

Author Keywords

Digital Fabrication; Creativity Support Tools; Design.

ACM Classification Keywords

D.2.2 Design Tools and Techniques: User Interfaces.

INTRODUCTION

Digital fabrication has been celebrated in recent years as a catalyst for shifting our design and manufacturing away from mass production; and into a "market of one" paradigm where we can make "almost everything" [5]. Its impact has been increasingly discussed within the HCI (human-computer interaction) academic field, and many innovative digital fabrication tools have been proposed to facilitate creative "making" endeavors [2,8,17,20]. Certainly, mechanical engineers and industrial designers benefit greatly from the advance of digital fabrication tools and processes—3D printers and laser cutters are employed as rapid modeling tools embedded within the professional design process. With the democratization of digital fabrication machines, 'making' with the technology is now accessible to amateurs and novices in the design field as well—from design students in college, to the STEM (Science, Technology, Engineering, Mathematics) classroom in primary and secondary schools. Professional, novice, or amateur designers, are now equipped with the means to fabricate and test ideas rapidly at a relatively low cost, and at a much earlier stage of the design process. However, just like any new tools, integrating digital fabrication into the design process is often a trial-and-error process—such as specifying the right joints and parameters for different materials during laser cutting.

Our research is concerned with the use of laser cutters as a model making tool embedded in the industrial design process. We focus on laser cut assemblies and the task of designing joints between different parts of such assemblies. Many of the insights shared in this paper were derived from our observations and interactions with students at the School of Industrial Design in Georgia Tech. Through this research, we developed *Joinery*, a toolkit that supports designers by responsively generating parametric joints on their digital drawings. *Joinery* supports fabrication awareness by providing six customizable joint profiles for a variety of materials and design needs (Figure 1), while remaining neutral to the process/outcome. Through *Joinery*, we aim to simplify the task of creating laser cut assemblies through automating joint design; improving the efficiency and expanding the diversity of models that designers can make with the laser cutter.

This paper describes our development of *Joinery*, Firstly, we outline the challenges and related work that inspired *Joinery*. Secondly, we describe the system's development and discuss its contributions. Thirdly, we evaluate the toolkit in action through its deployment in an interactive products class. Lastly, we discuss our findings and *Joinery's* impact on rapid modeling through laser cutting.

MOTIVATION

The word *creativity* stems from *creō* in latin—"to create, make, produce"—and digital fabrication machines like laser cutters and 3D printers have been envisioned as tools that will empower such creativity-through-making in STEM and design circles [2,5]. We want to push the fabrication limits of laser cutters, and the diversity of objects that our students and other designers can create with them.

Laser cutting and 3D printing are two digital fabrication processes widely employed in our school for model making. Though the laser cutter is limited to fabricating flat parts, 3D objects can be accomplished through bending, joining and stacking the 2D parts [3,8,12,22]. Many commercial goods are manufactured with this logic—flat packed objects, furniture and garments, are all produced from assembling a flat pattern. We observed that laser cutters are the main workhorse of our digital fabrication lab. As a subtractive 2D process, laser cutting is often more efficient than 3D printing's additive process [11]. As such, larger parts are typically built with the laser cutter, while 3D printing is employed for smaller, more intricate details [1]. With its efficiency and versatility, students in our school use laser cutters to fabricate a wide spectrum of models, including electronic enclosures, wearables, soft goods, furniture, and product forms. However, despite its ubiquity, designing and fabricating laser cut assemblies is still a complex task, especially for novices to digital design and fabrication.

Figure 2 illustrates the design to fabrication pipeline for laser cut assemblies. Computer-aided design (CAD) has been identified as a critical skill for digital fabrication proficiency [7,10]—however, the same skill has also been identified as a big barrier for novices [8,10,14,17,20]. 3D modeling in particular presents a steep learning curve to beginners. We observed that our students take different CAD approaches during the digital design phase. Some students are more proficient in 3D modeling (Figure 2A), and employ tools such as *Solidworks* [24] or *Fusion 360* [25]. However, most students stick to 2D drawing tools like *Illustrator* [26] and *Inkscape* [27] to create the files for laser cutting (Figure 2B). These different digital design approaches converge as designers approach the preparation phase for laser cutting (Figure 2C–F).

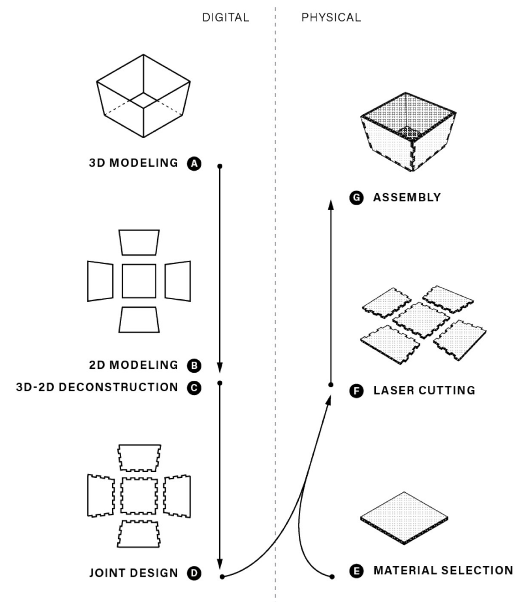

Figure 2: Pipeline for creating laser cut assemblies. Joinery tackles fabrication-aware joint design.

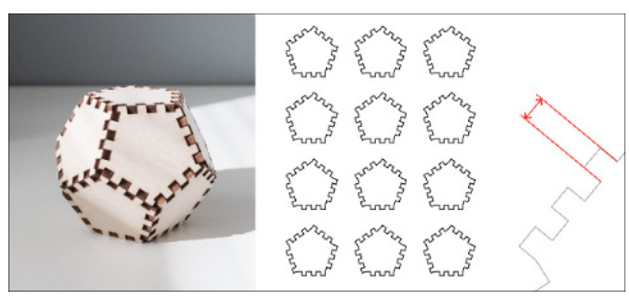

Figure 3: Adjusting the fit of the parts in this assembly involves changing the size (in red) of every finger joint.

Joint design (Figure 2D) falls within this converging zone, and is a critical task within the pipeline of creating a laser cut assembly. Joints hold the assembly together, transforming the flat laser cut parts into a functional structure. Joint design affects assembly efficiency—joints which require adhesives typically need more time than joints which provide an inherent connection. Joint design is also interdependent on many other factors in the pipeline; particularly, material properties with respect to laser cutting. Furthermore, joint design can be a tedious and complex task. For instance, tightening the fit between the dozen different parts of an assembly, or changing the type of joint, can be daunting not only for novices, but professionals as well, when each detail has to be reworked (Figure 3) [11]. Unfortunately, most CAD tools were not developed for laser cutting—and tools like *Illustrator* which novices gravitate to were created primarily for digital publishing and graphic design, not industrial design or engineering. Designers are thus required to independently integrate fabrication awareness into the digital process before fabricating with the laser cutter.

These barriers manifest in different ways that affect laser cutting's role as a rapid model making tool in the design process. Faced with these challenges, we observed that many students "make do" by downloading or customizing existing designs to suit their project needs. *MakerCase* [28] is a popular web application among students—it generates the fabrication drawings for a box from user-specified dimensions with all the necessary joints. With its level of convenience, we see the finger-joint-laser-cut-box emerge as the de facto standard for electronic enclosures in our school as well as online making communities (Figure 4).

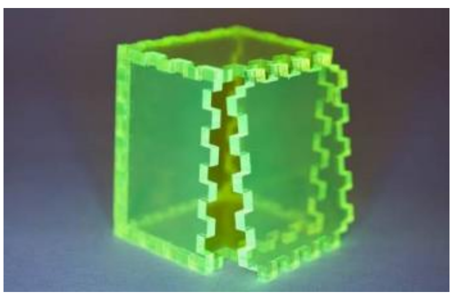

Figure 4: Acrylic box with finger joints on Thingiverse[1].

This culture of "making do" and appropriation is not an isolated phenomenon. Researchers who quantitatively analyzed *Thingiverse* (a popular online repository for 3D models) reported that customizable designs, which account for 2% of all "things", were responsible for generating 42% of all the models uploaded onto *Thingiverse* [14]. As design educators, we are concerned with this echo chamber fed by digital fabrication's own community—a state which "encourages designs to favor replication and sameness" [20]. Such a culture trivializes digital fabrication as a mere extension of mass production [2], and disables its potential as a creative and inventive tool within the design process.

In addition, despite the machine's capability for operating on a wide range of materials, the digital-physical gap results in the same materials being used in almost all laser cut models we see at our school. Basswood, acrylic or cardboard become laser cutting defaults as they are well documented and used pervasively both within local college labs and online making communities—creating a self-perpetuating bias when selecting materials for laser cut assemblies.

We see an opportunity to address the task of joint design for laser cut assemblies, and to facilitate the iterative model making process and fabrication awareness between digital design and physical materials. In addition, we want to expand the material vocabulary of our students as they explore their ideas through laser cut assemblies.

RELATED WORK

While we are motivated to address the challenges observed at our school, we are also inspired by emerging digital fabrication tools developed by industry and researchers in response to making with the laser cutter.

Fabrication-aware Design

Many professional CAD tools for architects, mechanical engineers and industrial designers incorporate fabrication constraints into the digital design activity [18]. With the democratization of digital fabrication, there is an emerging set of tools that incorporate such fabrication-aware design for non-professional users. Systems like *Plushie* [9], *SketchChair* [17] and *Marvelous Designer* [29], offer real-time feedback on the 2D patterns required to assemble the 3D design. *FlatFab* [8] offers another approach by constraining users to design 3D assemblies with planar sections, ensuring that they can be fabricated via laser cutting. In addition, both *FlatFab* and *SketchChair* provide simple physics simulations for users to evaluate the structure of their designs.

3D to 2D to 3D

Commercial tools like *123D Make* [30] and *Pepakura Designer* [31] automates the deconstruction of 3D models into 2D modules for cutting and assembly. Beyond a single 2D cutting process, researchers have proposed systems which deconstruct 3D models into a blend of 3D printed and laser cut parts. *Platener* [1] is a notable system within this category. Through *Platener*, designers can fabricate a design detail in higher resolution via 3D printing, while efficiently building the rest of the object with laser cut parts. Furthermore, *Platener* generates the required joints between the different parts of the assembly.

Augmented Laser Cutting

Systems like *LaserStacker* [22] and *LaserOrigami* [12] extends the laser cutter beyond cutting or etching materials, extending its capabilities to welding and heat-bending acrylic sheets. Similarly, laser cutting has been augmented with 3D printing concepts in the development of hybrid machines that cut and stack layers of fabric to produce soft

[1] http://www.thingiverse.com/thing:448592

3D objects [15]. These innovative systems support the complexity of objects that laser cutters can fabricate by harnessing different material properties. Besides augmenting machine operation, others have innovated on materials for laser cutting. *Foldem* [3] is a hybrid material which has varying properties across different layers. This enables it to remain rigid, bend or fold depending on the depth of the laser's cut.

Joints and Connections

123D Make, *SketchChair* and *FlatFab* generates connections in the form of slots to assemble the parts together. Other joint systems include the tab-and-glue connections found in *Pepakura Designer* and *CardBoardiZer* [23], as well as the common finger joint found in connections generated by *MakerCase* and *Platener*. Besides incorporating joints into part design, they can also be fabricated as separate components, such as the articulation pivots in *CardBoardiZer*. Laser cutting has also been explored together with fastening techniques found in traditional craft; notably in Tsaknaki et al.'s research on leather as a material for tangible interfaces [21].

Opportunities

Systems like *Plushie* and *SketchChair* constrain users to a specific outcome, while systems like *FlatFab* constrains users to a particular modeling process. While their specificity provides a useful sandbox for novices to explore the digital design and fabrication process, they may become too restrictive as users mature. *Joinery* is inspired by these systems, and applies fabrication-aware features for laser cut assemblies while remaining neutral to the process/outcome. In addition, many systems discussed above target a narrow class of materials, and consequently offer joint solutions specific to those materials. *123D Make* and *Platener* for example, focus on deconstructing 'hard' objects, while *Pepakura Designer* focuses on paper assemblies. This reinforces our goal to expand a designer's material vocabulary for the laser cutter. *Joinery* thus takes a material-driven approach to address the implementation of joints for laser cut assemblies.

JOINERY: SYSTEM DEVELOPMENT

We developed *Joinery* as a parametric joint generation toolkit to facilitate creating laser cut assemblies. Through Joinery, designers simply define connections between parts of an assembly, while the system generates the joints. Designers can select from a library of joint profiles developed for different materials. As these joints are parametrically modelled, they respond globally to changes—removing the need to manually edit each joint. In the following sections, we provide the system's implementation, detail the joint profiles that we have developed, and describe a scenario employing *Joinery* as a creativity support tool.

System Walkthrough

Joinery is a web application written in JavaScript, and it extends the *Paper.js*[2] library for vector graphics scripting. The user interface was developed through HTML and CSS. Joinery takes SVG files as input; a standard for vector graphics and laser cutting. The system also exports laser cutting files in the same format. In addition, projects and joint parameters are managed as JSON strings for potential future plug-in or API development.

SVG Structure

Joinery adds joints to a design by generating paths within the source SVG's XML structure. Standard SVG notation is employed to ensure that files are compatible with processes before and after *Joinery*, such as editing the design pattern (Figure 2C) or nesting parts for laser cutting. Class names and object IDs are used to organize and access different components within the SVG as joints are generated over edge-pairs defined by the user (Figure 5). The original paths are labelled with a "joint" class, while two new groups are added to the SVG structure for each edge. Each group contains the joint details, such as 'folding' or 'cutting' paths. These joint groups point back to the original path via its index (ID = index + "_joint"). This structure facilitates joint and path organization both within *Joinery* and after export. Paths in the exported SVG are color-coded based on their class. This makes it convenient to further edit the SVG for laser cutting in programs like *Illustrator* and *Inkscape*, supporting operations like changing all folds to dashed lines.

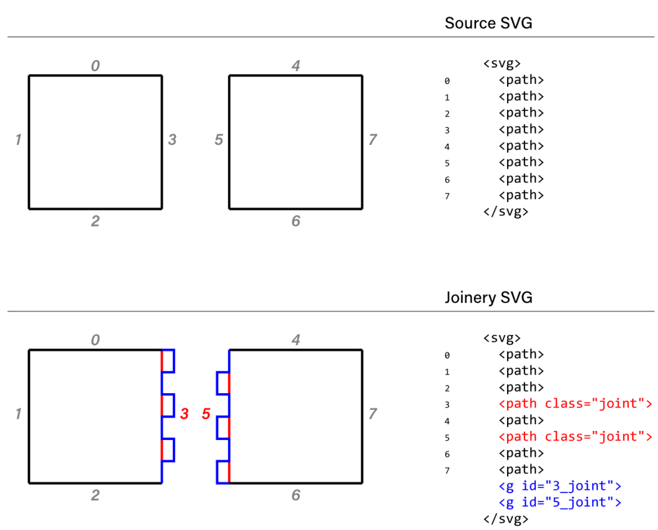

Figure 5: SVG structure for connections and joints.

[2] http://paperjs.org/

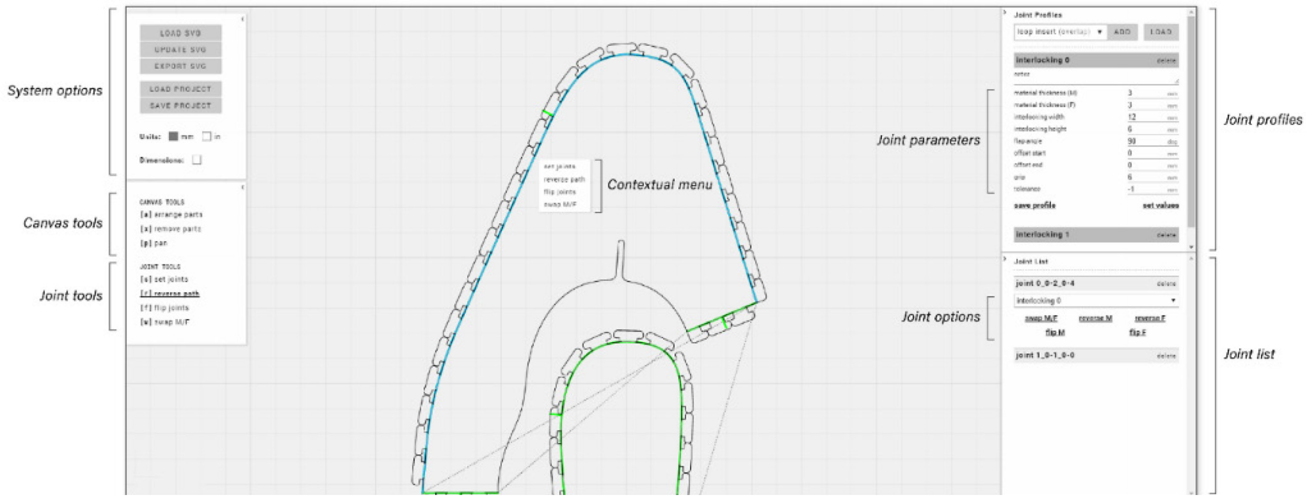

Figure 6: Joinery's interface.

User Interface

Joinery's graphical user interface is designed around a main workspace and joints are generated on user uploaded designs, mimicking the layout of 2D drawing programs like *Illustrator* and *Inkscape*. The left side menu provides system options and tools, while the right side menu is dedicated to joint profiles and joint details (Figure 6).

Applying and Modifying Joints

Users define joints by selecting a pair of edges. The system provides visual feedback by highlighting the edges and the connections between them after a joint has been defined. In addition, the normal to each edge is labelled, indicating the direction in which joints will be generated along the edge (Figure 7A).

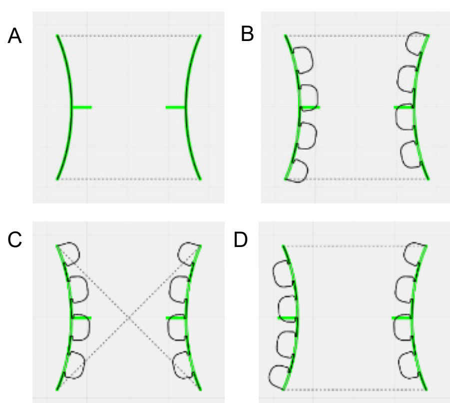

Figure 7: A: Defining a joint from an edge-pair. B: Applying a joint profile. C: Reversing an edge. D: Flipping an edge.

The interface organizes the task of creating connections into 'joint profiles' and a list of user-defined joints. Joint profiles refer to the type of joint and their parameters. *Joinery* offers six joint profiles, and each profile can be customized through its parameters based on material or design needs. The joint list contains all the edge-pair connections defined by the user. Joints are generated by applying a joint profile to an item in the joint list (Figure 7A–B), and *Joinery* updates these joints in real time. In addition, an edge can be reversed or flipped to fix the orientation of the generated joints (Figure 7C, D); these functions are supported through the joint tools, contextual menu and joint options interface. Multiple joint profiles can be added to the system for the same type of joint. For example, two 'interlocking' joint profiles can be added to the project, each with different parameters to be applied to different joints in the design. Similarly, the same joint profile can be applied to multiple joints.

Parametric Joints

Each joint profile is customizable from a set of parameters. These parameters enable the user to configure a joint profile to suit material, machine or design specifications. Joints are dynamic and easily updated due to their parametric nature. For example, increasing the "grip" parameter for an *interlocking* joint profile would give a tighter fit between two parts (Figure 8). Such parametric generation of joints thus simplifies the task of modifying each joint in response to design or fabrication changes.

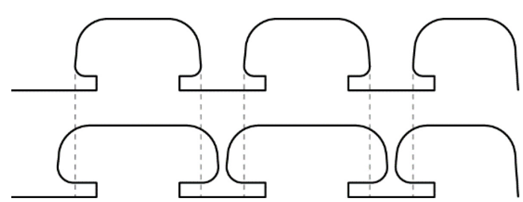

Figure 8: Increasing the "grip" parameter of an interlocking joint profile.

Exporting Joint Profiles

Joint profiles can be exported and saved for the next prototyping iteration, or shared with other users. We observed that information sharing is common practice among designers at our local digital fabrication lab; for example, machine settings for popular materials are

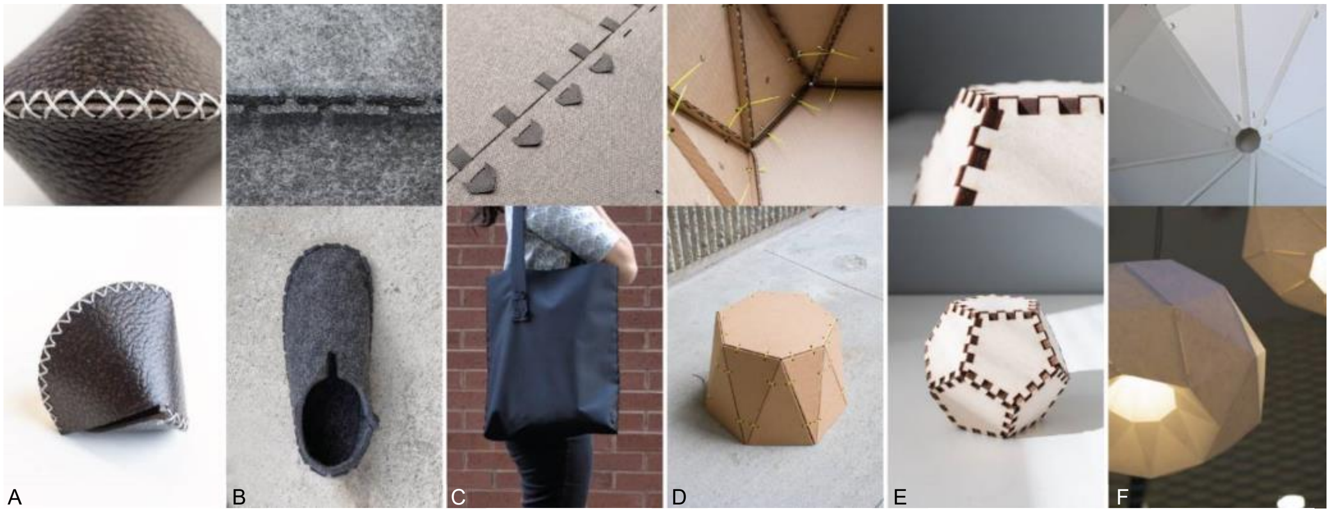

Figure 9: Laser cut assemblies with different joint profiles generated by Joinery. A: Hem, leather pouch. B: Interlocking, felt shoe. C: Loop Insert, nylon tote bag. D: Flap, cardboard table. E: Finger, wooden die. F: Tab Insert, paper lamps.

constantly updated and communicated. This feature was developed to extend such interactions. Joint profiles that have been optimized for a particular purpose (e.g. press-fit finger joints for 3mm thick basswood) can be shared with other designers who work with the same laser cutter. We envision that over time, this feature will facilitate a repository of joint profiles for different materials, specific to the needs of different fabrication labs and maker spaces.

Joint Profile Development

We took a material-driven, exploratory approach to develop joint profiles for the system. This echoes an emerging trend in HCI—investigating craft along with technology to inform new making and interaction possibilities [6]. Craft offers two different lenses to focus our exploration. Firstly, practices and techniques employed in existing craft can inspire the design of laser cut joints; such exploration is captured by Tsaknaki et al.'s research blending laser cut leather with different conventional and unconventional fasteners for interactive products made with leather [21]. Secondly, the interactions between materials and laser cutting can be investigated through the lens of craft practice, allowing "hidden" qualities to emerge [16]. *LaserOrigami* and *LaserStacker* for example, exploit material properties with the fundamental workings of a laser cutter, extending its capabilities to bend and weld acrylic. Our approach thus blends an extrinsic perspective of existing craft practices, with an intrinsic perspective of investigating laser cutting as craft. We explored laser cut assemblies with various joints and materials; and from this exploration, six different joint profiles for a variety of material and design needs were developed. Each joint profile was abstracted into a parametric model that exposes key variables for users to customize (Figure 1).

Hem

The hem joint profile facilitates stitching textiles by hand; in particular, hard to stitch materials like leather and felt. The holes generated reduces the effort required to 'pierce' the material during stitching, while guiding the user to stitch at regular intervals. Various stitching patterns can operate with this profile, such as cross-stitch (Figure 9A) patterns.

Interlocking

The interlocking joint profile extends the concept of finger joints, and connects two edges without the need for adhesives or external fasteners. The interlocking tabs work best on stiffer sheet materials like paper, soft plastics and thick felt, and they can be employed to join edges with and without surface continuity as seen in the shoe example (Figure 9B).

Loop Insert

Figure 10: Loop insert joint—nylon fabric and basswood.

Synthetic fabrics like nylon and polyester cut well with the laser cutter as the focused heat fuses the cut fabric and prevents fraying. However, while it is easy to cut such fabrics with the laser cutter, we observed that many students are not familiar with stitching fabric patterns together. The loop insert joint profile is an inherent joint designed to provide stitch-less connections for laser cut fabric parts. The tapered tip of this profile guides the inserts through the slits, while the hooks prevent them from slipping back. As a test, we fabricated a tote bag connected entirely with this joint (Figure 9C), and it was strong enough to hold the weight of a laptop computer with its accessories. In addition, we discovered that this profile offers an interface between fabrics and rigid materials (Figure 10); creating possibilities for multi-material assemblies with soft and hard details.

Flap

This joint profile is commonly found in flat pack carton boxes, and is also the default generated by *Pepakura Designer* and *123D Make*. *Joinery* extends this profile by introducing registration holes on the flaps—these holes guide users to connect parts together with fasteners like rivets or zip-ties (Figure 9D). The flap joint profile is ideal for paper-based materials, cardboard, even sheet metal.

Finger

With the right tolerance, press-fit finger joints hold a laser cut assembly together without the need of adhesives or other fasteners, and are commonly used with wood and acrylic. *Joinery's* parametric finger joints enable users to make fine adjustments to achieve a good press-fit. Furthermore, the system extends the typically perpendicular joints (Figure 3) to accommodate assemblies with walls meeting at different angles. By varying the interior angle parameter, users can create enclosures with more complex forms (Figure 9E).

Tab Insert

The tab insert joint profile was developed for paper-based materials or foldable plastic sheets. As an alternative to the flap joint profile, tab inserts require no external fasteners or adhesives. Tabs can be inserted 'blindly' (i.e. from one side), making it possible to fabricate closed 3D geometries such as spherical or toroidal forms (Figure 9F).

Shoe Design Sprint: *Joinery* as a Creativity Support Tool

We engaged in a week-long shoe design sprint using *Joinery* and laser cutting, with the aim of probing the system's role as a CST (creativity support tool). Nakakoji organizes CSTs with three metaphors: 1) 'Dumbbells' strengthens a user's domain knowledge to become capable without the tool, 2) 'Running shoes' augments the user's abilities to perform a task they are already capable of, and 3) 'Skis' offers the user new capabilities which were previously not possible [4,13]. We find these metaphors useful in describing the system we have developed, and reflect on our sprint with them in mind.

We began the process by researching on anthropometric considerations for shoe design, as well as different shoe types and their patterns. Our research led us to focus on slip-on shoes, and we chose to fabricate our ideas with polyester felt as it had a good balance between flexibility and structure. *Rhinoceros* (a 3D surface modeling tool) was used to model the shoe design around the dimensions of a researcher's feet, and the deconstructed 3D models were imported into *Joinery* for joint design. Designs were then laser cut and assembled. Five pairs of shoes were fabricated during this sprint; the first two focused on getting the right fit, while subsequent models explored different forms (Figure 11).

Joinery as 'skis'

Joint design for laser cut assemblies is not a new concept. However, *Joinery* offers a new experience by automating joint generation as well as enabling efficient customizations through its parametric joints. Our shoe models were assembled with the aid of interlocking joints generated by *Joinery*. Refining these interlocking joints to achieve a tight connection was a simple task—we iteratively improved the joints by customizing its parameters, while the system saved and replicated the best joints.

Joinery as 'dumbbells'

As we explored the process of fabricating with *Joinery*, we realized that we were developing heuristics for designing joints for different materials. Through the process of finding the right interlocking joint parameters for polyester felt, we learned that creating joints based on half the material thickness accommodates the felt's compression during assembly, resulting in a tight and robust connection. This is knowledge we can apply when modeling laser cut assemblies outside *Joinery*.

Joinery as 'running shoes'

The system certainly expedited our process of designing and fabricating shoes via laser cutting. Even though we are veteran digital designers who could have scripted the interlocking joints, or drawn them manually in *Illustrator*, *Joinery* simplified the task. Instead, we could focus our efforts on refining the shoe design. Nakakoji highlights that these CST metaphors illustrate not the tools per se, but the different relationships users have with tools. For us, the 'running shoes' metaphor best encapsulates *Joinery's* impact on our creative process. We set out to develop a tool that facilitates rapid model making through laser cut assemblies—and this system enabled us to fabricate five models to test our ideas over a short one week span.

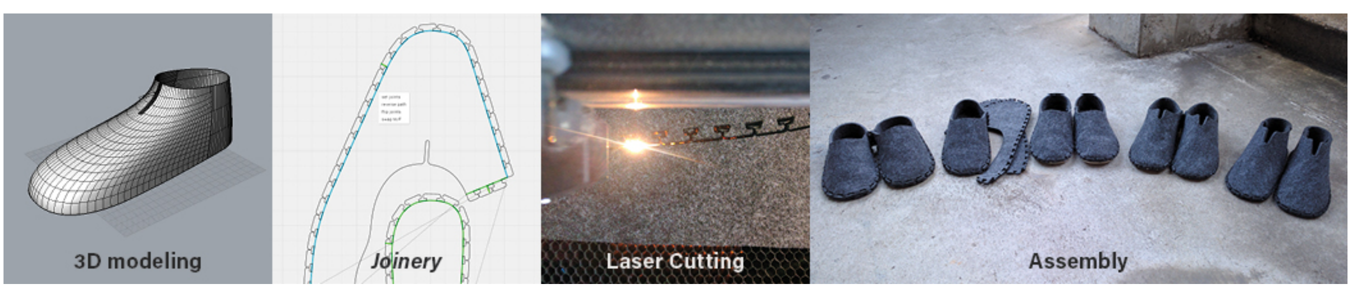

Figure 11: Shoe design process.

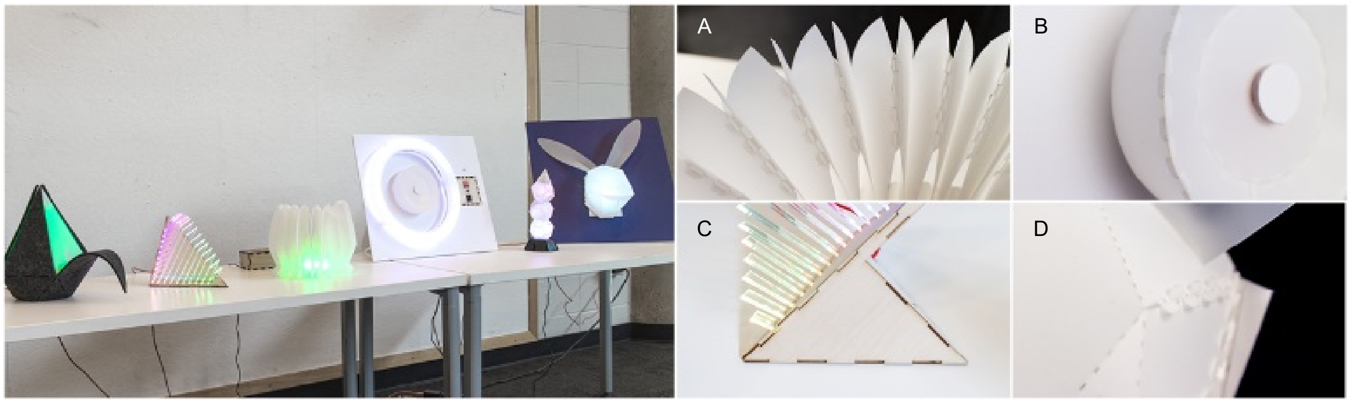

Figure 12: Interactive Lamps fabricated via laser cutting. A: Tab Insert joints for an accordion-like lamp. B: Interlocking joint for a knob. C: Angled finger joints for a faceted base. D: Interlocking joints for an origami animal.

Contributions

In summary, this paper claims the following contributions:

1. We developed *Joinery*, a toolkit that generates parametric joints for laser cut assemblies. Designers simply define edge-pairs as connections, while the system generates joints that respond to design and fabrication edits, thus mitigating the tedious task of redrawing the joints during the iterative process of creating laser cut assemblies.
2. We developed six classes of joint profiles for laser cut assemblies. Each profile is parametric and caters to different material and design needs, thus supporting fabrication awareness. Their parametric nature also facilitates the sharing of joint information between different designs and users.
3. We developed a novel joint profile (loop insert) and extended the applications of existing joint profiles for laser cut assemblies.

CLASSROOM DEPLOYMENT

We deployed *Joinery* in an Industrial Design class at Georgia Tech, focusing on the design and fabrication of tangible interactive products and interfaces. This iteration of the class had 13 students from Industrial Design and Mechanical Engineering. Among the students, 11 were undergraduates, while 2 were pursuing a Master's degree. Approximately half of the students had experience with fabricating with a laser cutter, while 3 students had experience fabricating tangible objects with embedded electronics. The class spanned fifteen weeks, and included work on four different projects. Of the four projects, the last three required students to fabricate and demonstrate a tangible interactive product. *Joinery* was introduced right before the second project, as part of a short in-class lecture on laser cutting as a rapid modeling tool. Our aim was to investigate how actual users will use *Joinery* 'in the wild', specifically with regard to the challenges and opportunities we observed for designing and fabricating laser cut assemblies.

We provided a fifteen-minute demonstration of the system to students in the class, and their initial response was encouraging. Students who had prior experience with the laser cutter were excited about the parametric joints. Recounting a past experience, one student reflected:

> *"I tried to make a wooden box with finger joints once, and the joints were always too loose, but I did not know how to edit the design to give [the box] a tighter fit. The system's [Joinery] breakdown of a joint into its parameters makes it clearer to me."*

While another student noted:

> *"I know that you can cut many materials with the laser cutter, but I never dared to since there wasn't any precedence. I feel more confident with the software [Joinery]."*

After the introduction to laser cutting and *Joinery*, students worked in 6 different groups to design and build an interactive lamp. This assignment required students to integrate the material and form of a product with its function (as a lighting device), and incorporate tangible user interactions.

We observed that choosing appropriate materials for the lamp was a challenge for most groups. While acrylic (a common material choice for laser cutting) offers decent light diffusion as well as structure, its rigidity limits form exploration. As students branched out to alternative materials, many of them arrived at *Mylar* drafting film (a translucent paper-like plastic sheet). While designing and fabricating with *Mylar*, many students employed *Joinery* to create interlocking and tab insert joints to connect different parts. One of the biggest advantages that *Joinery* offered students was the option of connecting parts without the use of adhesives.

> *"Glue affects the consistency of diffused light, while the tab [insert] joints gives the prototype [lamp] a really clean look."*

"For the rabbit head lamp [Figure 12D] it [interlocking joints] made it much easier to join the pieces together. Also the idea of avoiding glue altogether was fabulous!"

"I can easily take my model [Figure 12A] apart, change the location of the [flex] sensor, and put it back together."

Furthermore, *Joinery* facilitated students in their form exploration and interaction design process. With the hassle of manually drawing joints out of the way, many groups focused on iterating through concepts to integrate the form of the lamp with the interaction design. One group wanted to create an ambient lamp that reacted to the light and sound in the environment, and designed a cantilevered structure to mask the sensors (Figure 12C):

"I focused on creating the form [in Solidworks] and deconstructing it into flat parts, while Joinery generated the appropriate finger joints. In the past I only used the laser cutter for simpler boxes, this was much more complicated."

Another group designed an accordion-like lamp (Figure 12A) that users interacted with through collapsing and bending the folds:

"I could make this complex product just by assembling many individual parts together with the [tab insert] joint. It also helps me consider where the electronics and wires will go."

Some students that were initially skeptical about the strength of the joint profiles offered by *Joinery* were surprised at how robust the resulting assembly was:

"I'm surprised that the knob is strong enough for someone to turn [Figure 12B]. It is just thin paper and the [interlocking] joint. This is a lot more efficient than 3D printing."

Through this interactive lamp project, we also had the opportunity to test *Joinery's* joint profile sharing feature. One group encountered difficulty in achieving the ideal fit for the tab insert joints in their prototype. Over email, we were able to understand their issue, and sent them a joint profile with our recommended settings. In turn, that joint profile was shared among other students who were working with the same material.

Students continued to use *Joinery* beyond the interactive lamp project. For the final assignment, one group had an idea for a diaper bag that will alert babysitters when they forget crucial items. They fabricated their bag with thick polyester felt, and employed the interlocking joint to assemble the parts together without stitching (Figure 13). Their laser cutting to assembly process took less than two hours, after which they were able to focus on embedding and programming the electronics.

"It [Joinery] made the fabrication process a lot faster especially for felt as I didn't have to worry about sewing it. It also created cleaner looking final prototypes."

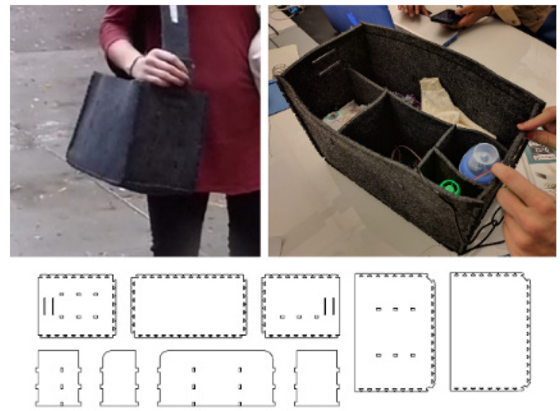

Figure 13: Smart diaper bag for baby sitters.

Reflection

The classroom deployment provided us with feedback which we used to improve *Joinery's* usability. Beyond that, it also gave insight into the approach that students took when designing and fabricating laser cut assemblies with *Joinery*. We reflect on students' interactions with the system, and discuss our findings with respect to the challenges that motivated this research.

Design to fabrication pipelines

Out of the 6 groups engaged with the interactive lamp project, 2 groups initiated the digital design with 3D modeling (*Solidworks*) while the other groups started with *Illustrator*. We observed that *Joinery* fit easily into these different processes. Whether it is 3D modeling, tracing an unfolded pattern, or repeating similar modules, *Joinery* tackled the task where these different pipelines converge; that is, preparing the 2D pattern for laser cutting (Figure 4). By remaining process/outcome-neutral, *Joinery* enabled students to work on a diverse range of inspirations (Figure 12) and embark on different modeling approaches; while the different joint profiles in the toolkit addressed their assembly needs.

Digital-physical negotiations

For more complex joint profiles like the tab insert, interlocking or loop insert, multiple parameters contribute to a joint 'character', such as ease of assembly, or fit. These parametric models proved to be too abstract for some students, who had a hard time relating parameter values to the material and joint character they intend to fabricate. This was mitigated through the joint export and share feature, where we provided a base parametric profile for students to modify. While we believe that this mimics the current fab-lab/maker space culture—where experienced users document material settings for others—we can certainly improve on the communication of *Joinery's* parametric models. For example, 1) different parameters in a joint profile can be semantically grouped based on how they affect different joint characteristics (e.g. fit, ease-of-assembly, 'springiness'), and 2) a library of materials can be built into the system for users to choose from (e.g. 100gsm *Mylar* drafting film).

We discovered that the back-and-forth process between *Joinery* and the laser cut parts challenged perceptions, and generated new insights for some students with regard to materials and laser cut joints. Quoting two students:

> *"I struggled with getting the [tab insert] joint to be strong enough to hold the form together, yet easy enough to insert. I didn't think that 0.1mm would make such a huge difference. The change is not even visible."*

> *"The individual tabs of the interlocking joint seems so flimsy and loose, but they are really strong as a group. Especially with a closed geometry [form]."*

Joinery automatically and responsively updates laser cut joints—even affording 0.1mm increments between iterations to get just the right fit. We believe this helps facilitate the iterations between digital and physical models for our students.

Some students struggled with visualizing the connections between parts in *Joinery*, and suggested a 3D view which simulates the assembly and joints. While this would be a technical challenge given the infrastructure used to build *Joinery*, this suggestion reinforces the question: how can we help design novices negotiate the gaps between digital design and physical fabrication?

Extending defaults

We were motivated to develop a toolkit that diversifies the material vocabulary and variety of objects fabricated with the laser cutter. The classroom deployment was successful in this regard—*Joinery* facilitated students' exploration of new materials with laser cutting (e.g. *Mylar*, leather, felt), and extended the design expression of familiar materials (e.g. basswood, acrylic). However, we reflect that *Joinery* might be extending laser cutting defaults for these students. During a discussion with them about *Joinery's* impact on their process, we discovered that many students selected materials based on the joint profiles that were available. A student who used the laser cutter for the first time reflected that:

> *"It [Joinery] may have subconsciously restricted the materials we could play with since we don't really know what does and does not cut in the laser cutter."*

Another student first decided to use the interlocking joint profile before selecting the material:

> *"We knew that whatever material we use, it would need to be flexible [for the interlocking joints], so that criteria was enough to choose the appropriate materials."*

Joinery opened up a wider range of materials for novices to explore when laser cutting; but we anticipate that it might become another precedent for novices to follow. This motivates us to continue pushing our investigation and development of digital fabrication tools that will support designers in independent creative exploration through digital fabrication. With respect to laser cutting, a logical next step for *Joinery* would be to introduce a 'joint editor' feature where designers can design joint profiles in response to new materials or design applications.

CONCLUSION

In *The Craftsman*, Sennett highlights that "sound judgement about machinery is required in any good craft practice" [19]. He extends *craftsmanship* to encompass even the art of building with digital materials (like operating systems) and delivering services (such as medical practitioners). Our process for developing *Joinery* resonates with this perspective on *craftsmanship*. We developed six joint profiles through a material-driven exploration. Some of these profiles bank on the intricate precision possible only with the computer-controlled laser, others expedite existing hand-making processes—all while considering physical material properties. We parameterized and packaged these profiles into *Joinery*, a toolkit to facilitate designing and fabricating laser cut assemblies.

From our investigation thus far, we believe that *Joinery* contributes to the growing ecosystem of tools for designing and making with digital fabrication. From our classroom deployment, we observed that *Joinery* simplified the task of designing joints for laser cut assemblies—expanding students' ability to explore complex forms, and offering them flexibility to use different materials. Our personal experience also points toward *Joinery's* potential as a creativity support tool not just for novices, but experienced designers as well.

We are keen to continue our research in this area, and plan to conduct several short and long-term design workshops on laser cutting and *Joinery* to investigate how different users engage with the toolkit in their creative process. In addition, we continue our exploration into materials and joints with the aim of expanding the diversity of objects one can design and fabricate with the laser cutter.

ACKNOWLEDGEMENTS

We would like to thank the class instructors for providing the space for us to deploy the toolkit, and the students for their time and feedback.

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