LaCir: A Multilayered Laser-cuttable Material to Co-fabricate Circuitry and Structural Components

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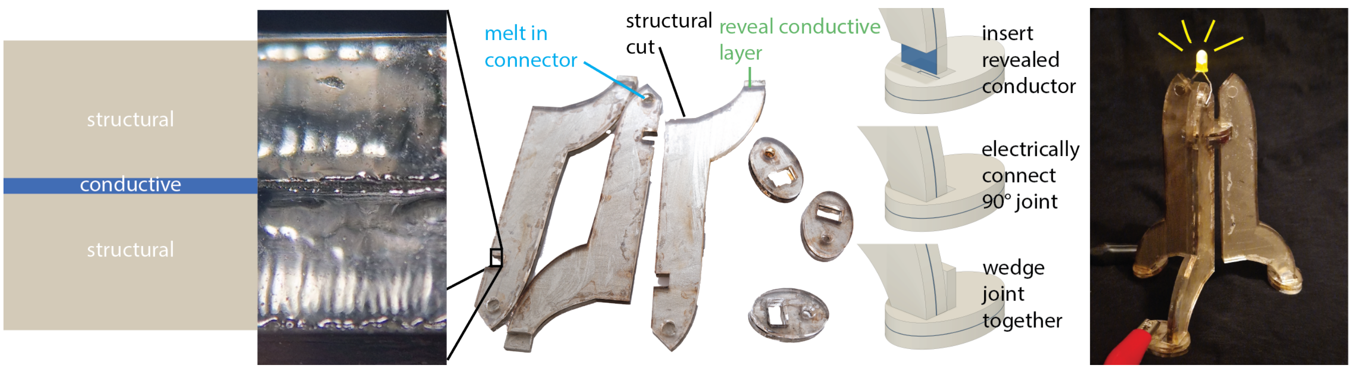

Figure 1: LaCir enables creating electrically-functional, structural objects on a laser cutter, through a laser-cuttable substrate that features a conductive layer sandwiched between two structural layers (far left schematic, centre left photo) which can be cut in various ways (centre). We explore 3D joints to help conduct through connections (centre right) for fully-functional objects (right).

ABSTRACT

Rapid prototyping is an important tool for designers, but many fabrication techniques are slow and create bulky components requiring multiple machines and processes to achieve desired device shape and electronic functionality. Prior work explored ways to ease fabricating shapes or designing electronics, but we focus on creating shape and electrical pathways *at the same time from a single material and machine.* LaCir leverages a three-layered, laser-cuttable material to incorporate circuits into the structural substrate of the design using laser cutters. Our substrate features a layer of conductive material sandwiched between thermoplastic sheets, allowing designers to cut electrical traces and assembleable, 3D object geometry in a single pass. We evaluate different composite materials, weighing their cuttability, ease of assembly, and conductivity; we also show using fully laser-cut joints as structural and electrical connections. We demonstrate LaCir's flexibility through several example artifacts.

CCS CONCEPTS

• **Human-centered computing → Interactive systems and tools**.

KEYWORDS

Prototyping; Digital Fabrication; Circuitry; Laser Cutter; Multi-material Stack; Circuit Joinery

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1 INTRODUCTION

To make interactive devices, today's designers combine various workflows and physical processes. Machines used to create devices' exterior shapes cannot, in general, also be used to make their electrical connections: this means designers must perform additional design work on the shape to accommodate printed circuit boards (also called PCBs), additional work in a different software tool to design the boards, and finally additional assembly work to bring together the fabricated shape and PCBs into a final object. This way of prototyping interactive devices, however, brings challenges. Outsourced PCB manufacturing can add significantly to iteration lead time. Prototyping device appearance on a consumer-level 3D-printer requires hours to render three-dimensional shapes at useful, human hand- or body-scales. Research has explored 3D printing the PCB-like components and the shape components together—e.g., with embedded wires [11, 27] or intricate printed geometry for sensing [24, 25, 29]—these techniques are still constrained to the fundamental speed limits of 3D printing, and not all applications require fully-3D circuitry.

Laser cutters, a faster fabrication technology, are an active research area as new techniques give them more shapemaking capabilities [8, 15, 31] and functionality [17], but these explorations either ignore circuit layers or require modification of the cutter itself. We extend these innovations, simplifying the construction process of interactive devices by relocating electrical complexity from the machine into the *material*. By enabling consumer-level laser cutters to produce 3D, electronically-functional devices in a single pass, we aim to democratize interactive device creation.

We introduce LaCir (Laser cut Ciruitry), a technique to fabricate three-dimensional, interactive devices. To achieve this, our technique creates what we call *structural circuits*: electrical pathways that are integrated into the structure—including across planes and through joints—of objects. While LaCir is inspired by previous work on laser-cuttable interactive devices and laser stacking [5, 12, 20, 32, 34], we go beyond prior work with our focus on solid, three-dimensional, and jointed laser-cut objects in lieu of single-piece, flat, stretchable objects [5] and enable constructing such devices with an unmodified, consumer-grade laser-cutter instead of requiring retrofitting [18]. Further, we systematically explore a variety of off-the-shelf dielectric and conductive materials that support our system goals.

We evaluate various material combinations for both structural and electrical purposes. Based on cuttability and ease of use, acrylic and silver paint perform best in most circumstances. We also explore laser-cut joinery that is compatible with LaCir, and show how with small modifications to expose additional layers it is possible to use fully laser-cut joints as both structural and electrical connections. We demonstrate embedding off-the-shelf materials, like magnets and screw inserts, as other methods of electro-mechanical joining. Finally, we show broader applicability of the technique by building various example devices, and close with a discussion of new opportunities created by this type of functional substrate paired with structure-focused rapid prototyping.

In summary, we contribute:

- A method for using sandwiched material consisting of two structural and one conductive layer to prototype electrically functional objects on a laser cutter.
- An exploration and evaluation of the characteristics of candidates for the conductive-and-structural substrate.
- An evaluation of laser-cut joinery and embedded off-the-shelf components as structural and circuit connections.

2 RELATED WORK

LaCir builds on recent trends in digital fabrication HCI research, exploring capabilities of geometry, materials, and electrical systems for rapid prototyping of interactive devices.

2.1 Geometry-Based Techniques

Early prototyping research used digital fabrication to create passive shells for components, but a growing body of work makes use of digital fabrication's ability to create custom geometries, both internally and externally, to enable object interaction. Geometry-based interactive devices like those LaCir can create rely on a relationship between intricate designs and material characteristics to sense users' activities.

Additive methods like fused-filament fabrication (FFF) allow for detailed, fully-3D internal and external shapes. Sauron [24] uses this capability to create custom internal geometry for computer vision-based tracking of user interactions, while Digital Mechanical Metamaterials [7] prints structures that guide force around a structure for logical operations. This technique can also be used with *multiple* thermoplastic materials: ./trilaterate [27] creates predictable 3D capacitive patterns. These are but a few of many explorations: 3D geometry, while difficult to design on a 2D screen, allows incredible design flexibility. However, 3D printers themselves are slow, so researchers have turned to laser cutting as a faster method for prototyping structure-based user interaction.

Interactive structures like living hinges, gears, or sliders can be made on laser cutters [16], and research has explored how to port these mechanisms across cutters (e.g., kerf-cancelling mechanisms [22], SpringFit joints [23]) and create 3D [1] or pseudo-3D [15] objects integrating them, thereby increasing laser cutters' flexibility in object manufacture. JigFab [13] and MatchSticks [30] use digital fabrication to create woodworking joints; we are inspired by these works as we consider joinery the LaCir substrate. These works focus on a single sheet of material at a time, but stacking is also possible: LamiFold alternates adding layers of material and cutting or removing parts in the laser to fabricate interactive devices. LaserStacker [31], on the other hand, selectively bonds multiple layers together by vaporizing and melting acrylic. We rely on techniques from Kerf-cancelling Mechanisms along with LaserStacker to work with our material substrate, but its capabilities go beyond the structure explored in those works to include electrical functionality.

2.2 Material-based Techniques

Other efforts exploit intrinsic properties of materials or design their own substrates to enable interactive capabilities in fabricated objects.

Foldem [3] designs a composite material with differing flexibilities per layer: one rigid, one bendable, and one flexible. By selectively cutting more-rigid layers and leaving only more-flexible ones, the meta-material's local malleability changes. LaCir focuses instead on *conductivity*.

Several others introduce substrates for cutting which focus on conductivity. iWood [34] creates plywood material with embedded triboelectric sensors to identify vibrations, while Olberding, et al.,'s cuttable multitouch sensor [19] uses patterned, printed electrodes to enhance robustness to cuts. Instead of focusing on avoiding damage to our substrate through cutting, we design it for selective, intentional cutting by the user, more in line with VoodooIO's flexible conductive substrate [32] or copperclad board. LASEC [5] and Fibercuit [35] introduce circuit-focused material similar to ours in which one layer is conductive and the other is not, but they target flat, stretchable, foldable, and wearable devices, and do not explore the structural requirements of 3D, assembleable, rigid, or jointed structures. Wessely, et al.,'s Shape-Aware Material [33] is designed so that cutting it *is* the functionality; instead of enabling digitization of physical work, LaCir uses a digital-first process for fabrication. In general, we share these works' vision for a mass-manufacturable substrate offering new properties in digital fabrication.

2.3 Prototyping Electrical Connections

As mentioned, 3D printers can extrude conductive thermoplastics in arbitrary 3D patterns [11, 27], but here we focus on rapidly-prototyping 2D and 2.5D circuitry more similar to what LaCir generates; future tools could help users understand speed/functionality tradeoffs like this.

One fast method of creating 2D circuits leverages an inkjet printer (or pen [6]) and conductive ink on paper [2, 4, 10, 20]. This enables flat shapes, foldable origami [20], or flat circuits that can be transferred to other developable substrates [4]. LaCir explores structural circuits with higher strength and durability than these interfaces.

Others make circuitry using the laser cutter. CircWood [8] carbonizes wood to create conductive traces on its outer layer. However, these traces are fragile, and the resulting conductivity depends on factors like humidity; LaCir's material is metal-based, which reduces these issues. We take inspiration from CircWood's use of traditional fasteners (e.g., screws) as conductive components in the preparation of our example applications. LaserFactory [17] uses silver ink (fused by the laser head) on acrylic sheets to create traces, but requires a heavily modified laser cutter and does not explore 3D joinery with this technique. In contrast with this, we design a material that removes the need for machine modification and which can include joints.

LaCir thus fills several gaps by uniting structural interaction with a designed material in which users can create electrical traces. Our technique and material require no modification to the prototyping machine, support creating jointed, structurally-sound objects, and accommodate traditional fasteners.

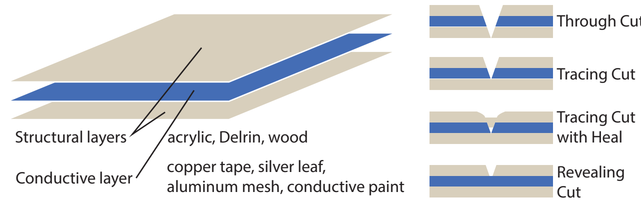

Figure 2: The LaCir substrate is composed of two structural layers sandwiching a conductive layer (left), and we tried various materials for each (left, bottom). We present four cuts to manipulate LaCir substrates (right): through cuts, tracing cuts, tracing cuts with heal, and revealing cuts.

3 LACIR

The LaCir workflow requires three main steps: digitally modeling the device, performing the cut, and assembling the components post-fabrication. These steps support the selective cutting and ablation required to expose, shape, and connect the conductive material inside our substrate that supports circuitry in the final device.

3.1 Digitally Modeling the Interactive Device

LaCir devices can be modeled in any DXF/SVG-generating CAD tool, like Autodesk Fusion 360, Inkscape, Adobe Illustrator, or Kyub [1]. We have developed a set of design primitives that work with our substrate, and which represent physical and electrical connections of various kinds along with the requisite cuts required to fabricate them.

3.1.1 The Cuts: Through Cut, Tracing Cut, Tracing Cut with Heal, Revealing Cut. To create both physical and electrical connections, we developed four cuts that manipulate one or more layers of the substrate (see Figure 2), based on the cuts presented in LaserStacker [31]. These operate on the material in vectors (i.e., lines). The particular settings needed to achieve each cut are material-dependent, and we explore them experimentally in Section 4.

Through Cuts are the most basic operation, and involve using one or more passes on the exact same vector to completely physically and electrically separate the two sides of the cut. This is the most usual action for laser cutting of all kinds. We represent these in **black** in our example images.

Tracing Cuts cut through only the first two layers of material, i.e., one structural and the electrical layer, at a lower power than the full through cut. These cuts make traces in the material, as it is electrically but not physically separated across the cut line. Optionally, if the structural layer is meltable, the top layer can be melted over the exposed conductive layer (by cutting again with an offset of $\approx$ .4 mm from the previous cut [31]) to seal it and improve its strength, creating a **Tracing Cut with Heal**. Heal cuts can also be used to seal additional materials inside the cut by first removing the cut centre, then inserting a new material, and healing around it. We represent tracing cuts in **red** in our example images, while tracing cuts with heal are **blue**.

Revealing Cuts are the least destructive useful cut: they physically separate only the top structural layer. A revealing cut can be used to remove the top layer of the substrate, thus exposing the

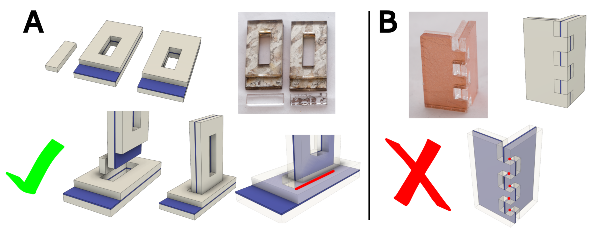

Figure 3: Comparison of joints. A: a completely laser-cut joint to use with LaCir, which uses a revealing cut and a wedge for assembly. The red line highlights a line of possible connectivity. B: A traditional finger joint. Connectivity is only made on the intersecting points between each of the fingers. This is highlighted with the red dots in the rendered picture.

conductive layer for joints or other connections to additional pieces. These types of cuts are **green** in our figures.

3.1.2 The Physical Layer: Shape, Joints, and Connectors. The shape of a LaCir device can be designed the same as any other laser-cuttable shape. Joining two pieces requires special consideration: in particular, to ensure that both their physical and electrical layers are adequately connected. This can be achieved through either modification of traditional laser joints, or through off-the-shelf connectors embedded into the material during the cutting phase.

Laser-cuttable joints include finger joints, t-slot joints, mortise and tenon joints, and more. These joints ensure good physical connection, particularly when paired with kerf-cancelling [22] or SpringFit [23] components. Electrical connections with these joints are, however, inadequate: the only connection is at a single point per finger where the two perpendicular conductive layers meet (see Figure 3, right), which risks burning the conductor away. We thus use our revealing cuts and a manual removal process to expose the electrical layer for a better connection, and take inspiration from Kerf-Cancelling Mechanisms to ensure good contact (see Figure 3, left). We use the removed part of the revealing cut to wedge the joint together more tightly from behind, thus increasing its conductivity. This type of design requires that the pieces being joined are perpendicular, as other orientations share the issue of reduced conductive layer contact. This requirement for orthogonality can be mitigated through the use of living hinges in a design, depending upon the materials comprising the substrate, a topic we explore later through experiments.

Off-the-shelf connectors can also be used within LaCir designs to create both electrical and physical joints between pieces, including interaction [9]. These types of connectors require a designer to use specific combinations of through cuts and tracing cuts, so they can connect to all substrate layers. We have explored screw inserts, neodymium magnets, and ball bearings (see Figure 4), which each have unique advantages and assembly techniques. Screw inserts use tiered cuts to expose the conductive layer, and are pressed in with a heated soldering iron after cutting: these enable screw-together parts. Neodymium magnets require a strong press-fit—as heated insertion can demagnetize them—but enable fast connection and disconnection. Ball bearings enable relative physical motion between connected pieces while still a maintaining conductive connection.

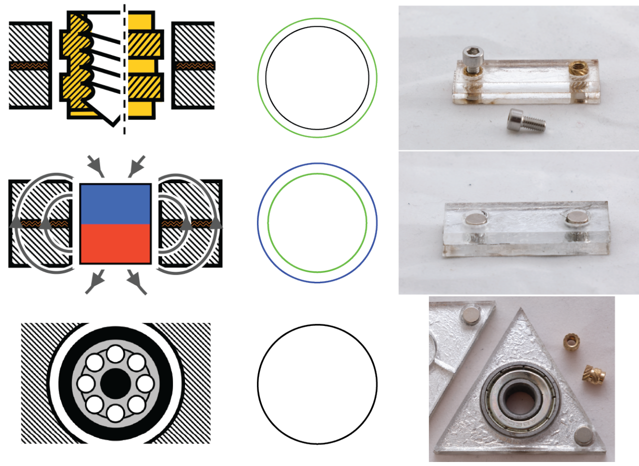

Figure 4: Example of external connectors used in LaCir to assemble separate layers while continuing the structural circuit: screw inserts (top), neodymium magnets (middle), ball bearings (bottom).

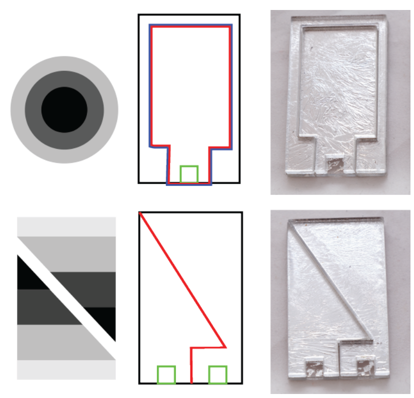

Figure 5: Example LaCir structural circuits with tracing cuts, comprised of a capacitive touch button (top) and slider (bottom).

3.1.3 The Circuitry Layer: Circuits and Structural Sensors. Tracing cuts (with or without healing) are the core of designing object circuitry, as they separate the electrical layer into individual segments. Unlike traditional PCB manufacturing processes, which are *additive*, laser cutters are *subtractive* in nature: the practical outcome of this is that circuit traces made with LaCir tend to look less like lines and more like areas, as removing all-but-a-line from an area is time– and energy intensive and creates fragile traces.

As the entire LaCir substrate is conductive, in addition to creating circuit traces it can be trivially used for capacitive sensing techniques, structured as buttons or sliders, like in Midas [26] or PaperPulse [21] (see Figure 5).

3.2 Fabricating the Design

To fabricate their design, creators must choose a substrate. We explored wood, Delrin, and acrylic as structural layers, and various tapes, leafs, meshes, and paints as conductive layers. Each individual material and combination imparts particular characteristics to the final product, which we further discuss in Section 4.

After selection, the substrate is placed inside the laser cutter for fabrication. For thermoplastic-based substrates, we do not use a pre-sealed stack: instead, we place structural and conductive layers into the cutter separately in an alternating fashion. The various cuts made weld the substrate together in a small-scale version of LaserStacker [31]. Wood-based substrate stacks are placed in the laser already glued. After fabrication, connectors are added, pieces are joined, and the device can be connected to power. In the interest of replicability, we provide cutter settings we used to create our structural circuits (see Table 1). While setups vary, designers can follow a protocol similar to Foldem's to tune these [3].

4 TECHNICAL EVALUATION

We explored various conductive and structural substrates, as well as methods of bonding, cutting, and joining them, to describe the design space of our layered substrate material. In essence, designers can pick and choose optimal components to achieve different goals in their objects: we envision a range of these combinations to be purchaseable in hobby stores and the like in the future.

We performed the same type of laser calibration process described in LaserStacker [31] to find appropriate parameters for each of our primitive cuts; all are described in the relevant tables. All our cuts, evaluations, experiments, and prototype applications were performed using an Epilog Helix 60 watt laser cutter, with a workbed of 610 x 457 mm.

4.1 Conductive Materials

For our substrate's conductive layer, several features are desirable: high conductivity, ease of cutting, capacitive touch capability, and the ability to conduct through laser-cut joints without conductive adhesive. We sandwiched between two clear acrylic structural layers the following materials: metallic leafs (silver[1], copper[2]), metallic tape (copper[3]), metallic mesh (aluminum[4]), conductive paints (silver[5], copper[6], carbon[7]), and ITO-coated PET[8] (see Figure 6).

As our substrate is handmade, the thickness of the electric material varies. The leafing material can tear or overlap, the brushed- and airbrushed paint can vary in thickness: this may affect joinery. To test the connectors and joints we created three fixed-geometry objects with each material (where possible) and measured resistance across them (length: 31 mm) three times. We then assembled the objects and measured resistance created across one and two joints (see Figure 7), also three times. Last, we cut a final test piece with tracing and revealing cuts, then attached it to an ItsyBitsy via alligator clips to determine if it was usable as a capacitive device.

Details are in Table 2. In general, the paints were not effective in joints, due to the fact that leafs do not ablate cleanly but instead fold over the edge of the structural layer, improving contact area versus paint. The paints also did not dry well when sandwiched between the acrylic layers, leading to their still being wet and therefore non-conductive even several days after sample was prepared. The aluminum mesh was not cuttable off the roll, but when we darkened it with black water-based paint and ran our laser on minimum speed we were able to cut it with about 95 % effectiveness (19 of 20 wires in our sample separated); this could be mitigated with multiple passes. The metal-based samples also came out of the laser cutter *very* hot, due to their increased thermal mass as compared to pure acrylic: we had to wait longer than normal (minutes instead of seconds) for them to cool on the bed for our inter-layer welds to solidify. Many samples delaminated and had to be reproduced for the conductor experiment, a failure we explore further in the next experiment (see Figure 8).

Additionally, we were interested in identifying the minimum separation needed between two tracing cuts, as when a single tracing cut is made the "folding" of the non-cleanly-ablated conductor (see Section 4.1) can create a short across the narrow gap. A too-narrow separation fails to solve the problem, and can also affect the structural features of the substrate. To uncover this metric, we created paired tracing cuts on a layered substrate made up of acrylic and silver leaf, separated from 0.1–0.4 mm, in 0.1 mm increments (see Figure 9). We then evaluated the conductivity between the two created layers of the structural circuit using a multimeter.

Our results show that the closest two tracing cuts can be in order to affect conductivity is 0.1 mm, and tracing cuts with this separation did not adversely affect the bottom structural layer.

4.2 Structural Materials

Different structural materials bring different characteristics and benefits to our layered substrate material (i.e., wood brings flexibility, while acrylic brings meltability) that lend themselves to different applications. To uncover which materials were most suitable for which applications and primitives, we carried out a series of exploratory experiments where we vary the structural layers.

These experiments were carried out using acrylic (both 1.5 mm and 3 mm thicknesses), Delrin (2 mm), and wood (3 mm). As all these materials are rigid by nature, our explorations focused on testing their capabilities to deform while maintaining their structural and conductive properties. To this end we created living hinges with these materials as the structural layers and silver leaf or carbon paint as the conductive layer, and also attempted to build springfit joints (see Figure 3, Figure 10).

The added thickness of a layered material does make soft, bendable living hinges difficult to realize, but all structural materials could do it. Significant bending can cause relative motion and delamination between the layers [28]. To compensate, designers can use thinner, more bendable material like Delrin. Additionally, we confirmed that combining acrylic parts using SpringFit [23] joints is not possible, which was expected as this technique was designed

[1]YYeglkas, ASIN: B0BG8754LD
[2]Skabmere, 0.1 mm
[3]Advance Tapes, AT525
[4]Amaco WireForm
[5]GreenStuffWorld https://www.greenstuffworld.com/en/electrically-conductive-paint/1087-conductive-paint-with-silver.html
[6]Lumilor https://shop.lumilor.com/collections/components/products/copy-of-placeholder-4oz-bundle?variant=28922946369
[7]Bare Conductive https://www.bareconductive.com/products/electric-paint?variant=37766230933684
[8]Adafruit https://www.adafruit.com/product/1309

		Through cut (m/s)	Tracing cut (m/s)
Conductive	Silver Leaf	0.183	0.427
	Copper Leaf	0.1525	0.366
	Silver paint (airbrushed)	0.183	0.427
	Copper paint (airbrushed)	0.183	0.427
	Carbon paint (brushed)	0.2135	0.305
	Aluminium mesh	Not possible	Not possible
	Aluminium mesh (darkened)	0.0305	Not possible
	Copper tape	Not possible	Not possible
	ITO	0.183	0.427
		Revealing Cut (m/s)	Healing Cut (defocused 4 cm) (m/s)
Structural	Acrylic (1,5 mm)	0.70	0.78
	Acrylic (3 mm)	0.61	0.61
	Delrin (2 mm)	0.70	0.80
	Wood (2 mm)	0.92	Not possible

Table 1: Speed settings for cuts and conductive and structural materials. All cuts use 100 % power, 5000 Hz frequency. Through Cut and Tracing Cut settings depend on the conductive material as its heat dissipation dominates the energy need, while the Revealing Cut and Healing Cut depend on the structural material as the conductor is unaffected.

Figure 6: Instances of all conductive materials explored with LaCir, fabricated using acrylic structural layers for visibility (copper tape and darkened copper tape, silver paint, copper paint, carbon paint, silver leaf, conductive thread, ITO). The conductive threads seen here did not work well, so we do not report formal experiments with them.

	Avg. resistance across 31 mm (Ω)	Avg. one-joint resistance (Ω)	Avg. two-joint resistance (Ω)	Capsense?
Silver Leaf	18	53	157	Yes
Copper Leaf	22	83	203	Yes
Silver paint (brushed)	33	35	58	Yes
Copper paint (airbrushed)	27	84	157	Yes
Carbon paint (brushed)	57	No connection	No connection	Too wet
Aluminium mesh	Not cuttable	Not cuttable	Not cuttable	Not cuttable
Aluminium mesh (darkened)	Not cuttable	Not cuttable	Not cuttable	Not cuttable
Copper tape	Not cuttable	Not cuttable	Not cuttable	Not cuttable
ITO	198	No connection	No connection	Yes

Table 2: Results of our exploration on conductive layers with their specific laser cutter settings for tracing and through cuts. We highlight the material's capabilities on sensing capacitive touch, and its average resistance within the cut object and through one and two joints. Materials which were not compatible with Capsense were too challenging to join to existing electronics or still wet (paint) or not cuttable (meshes, tape).

for wood. We note that all tested materials can create satisfactory LaCir substrates: there is no one *best* material. There is, however, a "best material for a purpose." For example, our experiments revealed that, due to increased flexibility, wood dielectric layers are suited to applications requiring mobility, while acrylic is better for rapid prototyping with melting and welding by the laser. Delrin is a balance: more flexible than acrylic, but slightly less meltable, which led us to focus more on acrylic in our tests due to our use of LaserStacking techniques.

Figure 7: For our conductive layer tests, we cut objects of fixed geometry (left) with varying conductive layers. We clipped them to an ItsyBitsy at the orange point and attempted to use the CapTouch library (centre). We then measured resistance across single parts, and through 1 and 2 joints at, e.g., the two joints between the red points (right).

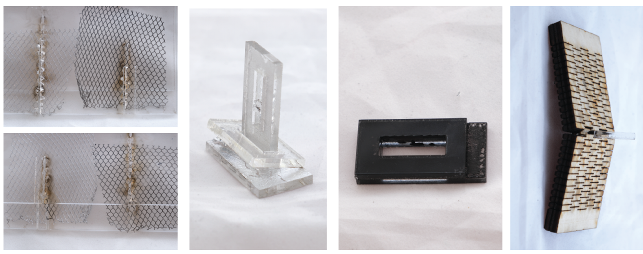

Figure 8: Failed examples from our conductors test. Aluminum mesh where some links are cut and some are not, and the acrylic structural layer is burnt (left). A silver leaf-based sample that delaminated after assembly (centre left). Carbon paint samples which are still wet days after sample preparation (centre right). A living hinge joint with one broken structural layer (right).

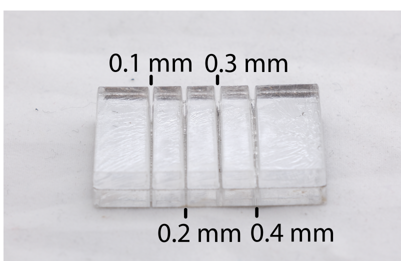

Figure 9: Example object from our explorations with tracing cuts separation distances.

4.3 Bonding Conductive and Structural Materials

With knowledge of different conductors, we also needed to know how they could combine with our various structural substrates. We created several combinations to explore lamination and cuttability characteristics: acrylic with all cuttable conductive layers, wood with metal leafs and glue, wood with conductive paints, and Delrin with silver paint.

We found that the thickness of a thermoplastic determines a lot about the strength of the bond; thinner plastic layers (or less-meltable plastic layers, like Delrin) create less welding material during the through cuts, leading to worse outcomes. This can be mitigated through applying additional materials post-fabrication, for example conductive glues, though this of course increases user labor and fabrication time. Some pairs of materials did not provide acceptable results: in our wood and copper stack we saw burning due to the heat mass of the copper.

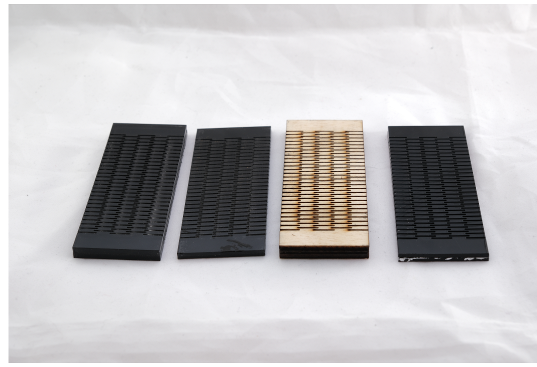

Figure 10: Sample living hinges created with different LaCir substrates. Left to right: 6 mm composite of acrylic and carbon paint, 3 mm composite of acrylic and carbon paint, 6 mm composite of wood and silver leaf, 2 mm composite of delrin and silver leaf.

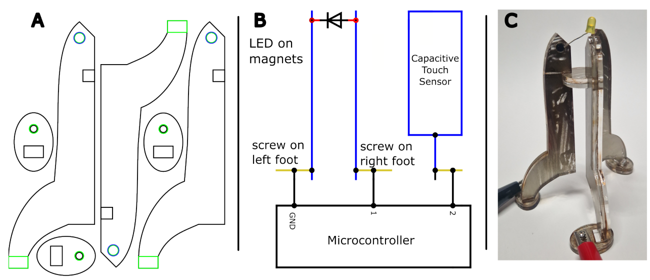

Figure 11: A lamp shaped like a rocketship, built from 6 individual pieces (A) connected by laser-cut joints and connectors. The lamp's circuit connects the micro-controller through two feet via healed-in screw inserts (yellow), up through the legs (blue), and to the LED with magnets (red) (B). The third foot and leg are configured as a capacitive touch sensor. Assembling and connecting the lamp lights it up (C).

5 APPLICATIONS

Below we present example devices to illustrate LaCir's utility and potential. All applications are fabricated from acrylic combined with silver paint, as this provided the easiest-to-work-with characteristics in our tests.

5.1 Rocket Lamp

Having a rocket lamp is the dream of every kid. In our LaCir lamp, we connect power at two of the rocket's "feet" to light an LED at its nose (see Figure 11). We use our special laser-cut joints between body parts, magnets to attach the LED, and screw inserts to enable alligator-clip connection to power. The entire rocket body is

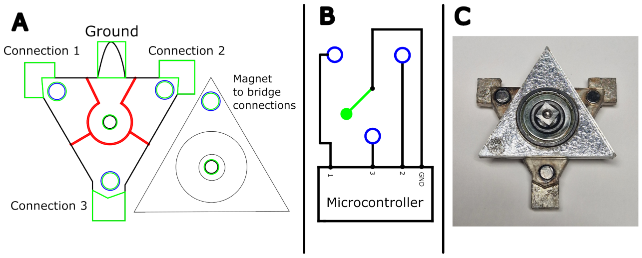

Figure 12: A wheel of fortune example application created with LaCir, comprised of individual pieces connected using ball bearings, screw inserts and magnets. The cut schematic shows tracing cuts (red) that separate the segments, and a donut-shaped cutout for the press-fit ball bearing insert (A). The circuit diagram highlights the top layer (green) that spins with a magnet on the end, connecting to one of three endpoints (blue) (B). This is visible in the fully assembled device (C).

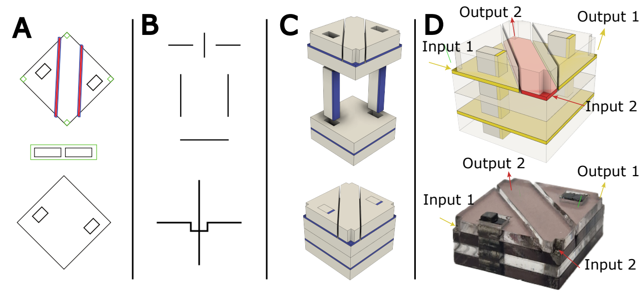

Figure 13: A multilayer PCB, built from 4 individual pieces connected by laser-cut bridging joints. The SVG file has four parts: the top layer, two legs that bridge the layers, and the bottom layer (A). Before assembly, the parts create 6 separate circuits, but after assembly there are two independent coplanar connections (B). The pieces slide together vertically into a single assembly (C), which creates two independent input/output pairs from corner to corner (1 is yellow, 2 is red, D).

conductive; we did not use any tracing cuts to guide power on particular paths, except that the third leg is designed not to short the circuit between the other two by using a non-conductive traditional finger joint. The third leg hosts a screw insert; its entire surface is a capacitive touch sensor to activate the LED. We fabricated this lamp in acrylic and silver paint, as its coloring gives an other-worldly feel to the design.

5.2 Wheel of Fortune Spinner

We also implemented an electric 'Wheel of Fortune' with our primitives (see Figure 12). This design enables spinning the wheel to create contact with a random base segment; the wheel is grounded and each base segment has its own power source—separated by tracing cuts—thus spinning completes one of three circuits. We use press-fit ball bearings and magnets to connect bottom side of the wheel to the base segments both physically and electrically.

5.3 PCB with Vias for Flyover Trace

To highlight the inter-layer joint capabilities and underscore the utility of tracing cuts, we prepared a PCB which features two vertical vias that together create a flyover trace (also called a bridge) (see Figure 13). Our PCB has 4 coplanar connection points, which are electrically connected in diagonal pairs. To allow for such a jump without a short circuit, we use a 2nd layer.

6 DISCUSSION AND FUTURE WORK

While we report on our initial exploration into a multilayered, laser-cuttable material for co-fabricating circuitry and structural components, we are also excited to note that there are many further possible avenues of research into the substrate composition and manufacturing technique. We also suggest future work on the design tools needed to help integrate structure and circuitry.

6.1 Compatibility with Existing Laser Techniques

We leverage a wide variety of existing techniques from lasercutting litterature, but future work should explore our substrate's compatibility with others, such as LaserOrigami [15] or Fibercuit [35]: anecdotally, we have found that the heat dissipation features of tested conductive layers complicate uniformly, simultaneously deforming both structural layers in a coordinated way, but future strategies may mitigate this.

6.2 Scalability

LaCir's substrates, in theory, are scalable to arbitrary sizes. In our exploration, we were limited by the sheet size of conductive layers we could purchase, as placing multiple sheets adjacent to each other resulted either in a missing electrical connection or a slight overlap which created unpredictable cutting results. Naturally, other structural considerations come into play at larger sizes (warping, reduced effect of edge-welding, etc.): a topic for future research and development. On the small end, we briefly explored integrating surface-mount components (SMDs) with our tracing cuts, but found that the relative sizes of executed tracing cuts (≈.3 mm) compared to SMD pitch along with both variability in our hand-assembled layers (e.g., torn leaf) and challenge in exposing our structural layers to solder heat made this difficult. An industrially-manufactured substrate and higher-precision lasercutter could mitigate this.

6.3 Non-independence of Structure and Circuitry

When using traditional tools that isolate the structural and circuitry design processes, the two sets of designs can be largely independent of each other (though generally circuitry is intended to fit inside of an object's structure). With LaCir, while it is possible to create multilayer circuitboards through alignment of multiple stacks of cut

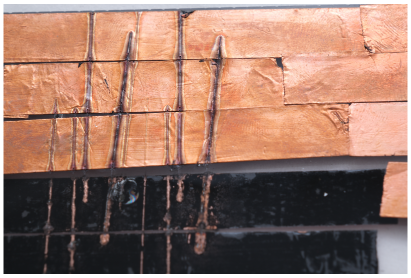

Figure 14: A stack of copper tape with acrylic which has been cut on a fiber laser: only the copper is cut, and it did not matter whether it was on top of or beneath the acrylic.

substrate, due to the nature of structural circuitry the two designs are somewhat more entangled.

6.4 Additional Materials and Fabrication Tools

We explored a variety of commonly-available materials to serve as structural and conductive elements in our substrate stacks. Some proved difficult to cut—a challenge which could be mitigated through using fiber lasers (see Figure 14), CNC mills, waterjet cutters, or other types of machines. These technologies would remove the possibility of applying LaserStacker techniques [31], but may offer other opportunities for unique substrate manipulation and may be less sensitive to small thickness changes in the conductive layer. Thicker metallic conductive layers may also make it possible to design objects with meaningful thermal transfer capabilities in addition to the electrical ones we explore [14]; the substrates our CO_2 laser can cut are too thin for this to be of much effect.

A conductive layer which can be selectively *melted* (similar to the behaviour of acrylic) by the laser would also provide interesting opportunities. Low-melting-temperature metals such as gallium could enable better circuit connections at piece boundaries and through joints.

6.5 Fabrication vs. Design Time

Use of LaCir's material stackups requires slowing down the laser's cutting beam to get all the way through, as the material is thicker and the electrically-conductive layers also tend to have heat-conducting properties. This leads to a slowdown of up to an order of magnitude, as seen in our settings table. However, this minor fabrication-time slowdown is dwarfed by the amount of design time spent in integrating tracing, joints, and other hardware cuts into the design. A future design tool could integrate features of e.g., Eagle[9] into Kyub [1] with flood-filling techniques that map circuitry onto laser-cuttable geometry, but this was outside the scope of our exploration into the possibilities of a structural substrate.

7 CONCLUSION

We presented LaCir, a technique for fabricating structurally-sound, jointed objects with custom embedded circuitry in a single pass on a stock laser cutter. We described the material substrate that enables this technique—a sandwich of structural and conductive materials—as well as our explorations into the possible stackups. Further, we measured the capabilities of these materials through a series of structural, joinery, and conductivity experiments, and demonstrated their use in a series of example objects.

[9] https://www.autodesk.com/products/eagle/overview

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