Spray and Etch: Personal Fabrication of High-Resolution Electroluminescent Displays

Chaoyi Wu
Computer Science
University of Bath
Bath, United Kingdom
cw2578@bath.ac.uk

James David Nash
Computer Science
University of Bath
Bath, United Kingdom
jn688@bath.ac.uk

Jason Alexander
Computer Science
University of Bath
Bath, United Kingdom
jma73@bath.ac.uk

Ollie Hanton
Computer Science
University of Bath
Bath, United Kingdom
oph33@bath.ac.uk



Figure 1: Spray and Etch enables personal fabrication of high resolution electroluminescent (EL) displays through (A) additive spraying and (B) subtractive laser etching. This enables (C) rapid fabrication of high resolution pixelated matrices (0.4mm pixel width), (D) high resolution EL segments and (E) base electrode etching on non-planar surfaces for custom interactive devices demonstrated with a prototype of an interactive nail display.

Abstract

We present *Spray and Etch*, a novel personal fabrication method for bespoke-shaped high-resolution displays through alternating spraying of electroluminescent materials and laser etching. Personal fabrication of custom shaped displays has opened the door to fully free-form interactive devices. However, developments have been limited to low-resolution segmented displays, monochromatic output and methods that are prohibitively complicated for non-specialists. Spray and Etch combines low-cost deposition methods (airbrushing) and the use of common makerspace infrastructure (laser etching) to address these limitations, enabling high-resolution displays through easy-to-use methods. We contribute eight performance characterisations of this process and demonstrate its potential with a functioning passive matrix display that can dynamically display images and video. We show that Spray and Etch has the potential to be expanded to both non-planar topographies and dynamic multicolour displays. Improvements in resolution and usability through Spray and Etch represent a step change in the personal fabrication of free-form displays.

CCS Concepts

• **Human-centered computing** → **Displays and imagers**.

Keywords

Electroluminescent, Personal Fabrication, Laser etching, Interactive devices, Display Fabrication

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1 Introduction

Personal fabrication of high-fidelity displays facilitates the on-demand design and creation of interactive devices with forms that fit their function. However, display technologies still face significant hurdles to realisation within the personal fabrication context [19]. Recent innovative works have introduced a broad range of

methods and materials covering novel means of display fabrication, but these are often limited in their usability by non-specialists [16, 37] and by the resolution of output devices [24].

Current personal display fabrication approaches [19] that manipulate active materials, are largely limited in resolution, specifically focusing on segmented, low-resolution output devices [21, 27, 33]. Many works explore the use of either hand-held or craft-based techniques [16, 37, 52]. While these are available to a wide range of users, and can build on existing skill-sets to help develop material understanding, the lack of programmatic material manipulation limits the replicability, accuracy and reliability of processes. Further, downsizing traces and pixels, required for high resolution, is only possible through high-precision automation. Precision-based programmable methods for electronics manufacturing used in industry and clean-room labs, such as photolithography and electron beam lithography, require high-temperatures, inert gas environments and inaccessible equipment precluding their use for personal fabrication.

We develop a new personal fabrication process for high-resolution electroluminescent displays: "Spray and Etch". We propose an alternating production workflow between additive hand-held spraying of electroluminescent material and subtractive programmable removal of material using an unmodified laser cutter. Both spray deposition and subtractive laser removal (known as laser ablation or photo-ablation) are used in manufacturing [38, 41]. However, their combined use for high-resolution personal fabrication of electronics has not been developed. To implement these technologies a personal fabrication environment [4], such as in a hackspace or maker space, a novel fabrication method must have minimal impact in terms of skill-threshold, failure rate, complexity, space and cost. We propose a combination of low-cost spraying and unaltered hardware (laser cutters[1]), both increasing the fidelity of output devices but also keeping the process accessible to the non-specialist.

Spray and Etch builds on the hand-held sequential deposition of active materials introduced in Sprayable User Interfaces [21, 52], with the novel addition of subtractive laser etching interspersed between spraying processes. Building on previous work that implements use of lasers in functional fabrication [17], we present an unprecedented resolution of fabricated displays that can be achieved by laser etching directly through sprayed paint layers in a process we call *direct laser etching*. Through extensive scoping, we further identify that it can be used to remove single coats of paint within a layered structure which we term *selective etching*. By combining these methods, we can produce high-resolution passive matrix display structures.

This approach goes beyond masking, removing the human-centric high-dexterity, time consuming masking methods that are not scalable and have limitations in reliability. We further demonstrate this approach's applicability to non-planar surfaces by modulating laser power and speed to compensate for differentiations in laser focal point. We also show the scope for its use in the creation of configurable multicolour display structures, by etching away different additively sprayed EL phosphors to create closely adjacent coloured pixels. This paper contributes:

- The Spray and Etch fabrication pipeline, an alternating use of handheld spraying of electroluminescent materials with laser etching to produce complex electronic structures using unaltered makerspace-appropriate tools.
- A control circuit and electrode attachment procedure for fabricated passive matrix displays.
- Eight performance characterisations exploring the technical constraints and limitations of Spray and Etch and explorations of the feasibility of the creation of multicolour and non-planar displays.
- Five technical demonstrations of outputs from the Spray and Etch process, implemented as both segmented and high-resolution passive matrix pixel displays as well as showing preliminary explorations into multicolour pixel fabrication and the feasibility of non-planar surfaces.

2 Related Work

2.1 Personal Display Fabrication and Spraying

The DisplayFab framework describes challenges and opportunities amoungst which further work on personal fabrication of displays can be situated [19]. Key among these challenges are the integration of design practices, refinement of fabrication processes and the fidelity of output devices. PrintScreen [37] introduced electroluminescent (EL) material to personal fabrication within HCI using screen printing approaches to accessibilise display fabrication with high resolution planar outputs. In Objectskin [16], Groeger *et al.* perform initial forays into exploring non-planar EL deposition while Wessely *et al.* explore deformable structures in Stretchis [53]. Klamka *et al.* demonstrate an extensive exploration into the use of EL through screen-printing to create digital paper [27].

We identify a key set of works that explore the deposition of active materials on free-form surfaces for the purpose of display fabrication, most recently focused on spraying. Photochromeleon [25] explores the cohesive deposition of photochromic material activated with an external stimulus, thereby not requiring precise traces. In tandem, ProtoSpray [21] and Sprayable User Interfaces [52] have introduced the state-of-the-art spray deposition of EL material, building on the development of technologies beyond personal fabrication [30, 47] and hobbyist implementations [29]. Both works explore alternatives to conventional masking. Masking is time-consuming, requires high dexterity and skill to implement and has fundamental limitations on pattern and fidelity of resolution. Sprayable User Interfaces explores large scale designs with projection for guidance and precut templates, enabling expressive creation but limiting precise resolution. ProtoSpray uses conductive thermoplastic tying resolution and production capabilities to FDM 3D printing with a maximum resolution of approximately 2mm per pixel. Beyond displays, the spray deposition of conductive paint has taken different forms. In MaskCircuit [18], Han *et al.* implement the laser etching of protective covers on acrylic sheets to enable easy creation of sprayed circuits, requiring finesse in mask removal and are limited to 2D surfaces and acrylic substrates. In MechCircuit [13], Feng *et al.* implement magnetic structures with sprayed conductive paint and added electronic components. These works provide a foundation for spray deposition of conductive material as a means to fabricate circuitry available within personal fabrication

[1]In a preliminary search we carried out of maker spaces in the UK, we found that 68% of the hacker spaces evenly distributed in major cities have laser engraving capabilities.

with EL as an optimal display fabrication material. However, current work is largely limited to segmented displays with fabrication process constraints, such as the dexterity needed for masking.

2.2 Custom High-Resolution Electronics Creation

There are a range of tools a systems to produce custom electronic structures, however most are limited in their use within personal fabrication due to cost, complexity or required knowledge. Commercially, the Voxel8 represented an innovative solution to producing low-resistance electronic devices [51] by combining FDM printing with automated silver paste dispensing, although this tool is no longer in production (but represented a process accessible to a maker space). For higher-level custom-form device fabrication, Optomec provides an industrial solution. The Optomec 6-axis aerosol jet [38] can precisely deposit conductive traces onto irregular objects with a reported precision of up to 1 micron [39]. However it is prohibitive in access (requiring nitrogen lines, costing >500,000 USD and requiring high-skill technical operation). Tools such as the Sonoplot [49] allow for the prototyping of fine electronic structures, departed from their integration within larger physical objects. Meanwhile systems such as the Asiga Max X [1] allow for the creation of functional structures through microfluidics beyond conventional 3D printing. Despite the strengths of these products, we identify the prohibitive nature of these systems and advocate for use of both existing fabrication hardware such as laser cutting and easily accessible technologies such as handheld airbrushing to achieve competitive output device infidelities. Within electronics manufacturing, we highlight laser ablation as a method for producing high-resolution electronics rapidly [46]. Typically this approach is limited to manufacturing methods, and to our knowledge it is not explored in a personal fabrication context with the closest work encompassing contributions such as that of Qin *et al.* exploring laser ablation for flexible circuit boards [41].

2.3 Laser Cutters within Personal Fabrication

Laser cutters with the ability to laser etch are commonplace within makerspaces due to their strengths in rapid prototyping and production of robust output with high precision. HCI research has broadly explored developing improved functionality in the context of digital fabrication of inactive structures [5, 26, 43, 45]. Roumen *et al.* explore the portability of laser cutting both in commutability between systems [44] and mobility [42]. Mueller *et al.* explore the scope for rapid assembly in Laser Origami expanding the potential of prototyping through laser cutting [35]. As part of their analysis of fabrication workflows, Fossdal *et al.* identify the linearity of laser cutting and most notably fundamental limitations such as control over z-axis movement which helps us bound areas of this project [14]. Groeger *et al.* present a method for instantly producing Stretchable Circuits with a resolution of up to 3mm on deformable substrates [17]. Laser Factory explores the sintering of conductive material combined with subtractive cutting using a modified laser cutter [36]. Most recently, in their work "LaCir", Buch's *et al.* innovate a new triple layered material with a laser cutting process to produce objects that are functional and structural [7]. The laser etching of masks is built on other work such as Feng *et al's* [13] which uses laser cutting of acrylic stencils. Beyond this body of related works, the scope for using laser etching to remove hand-sprayed active material is open to development with the high-resolution potential of laser etching (<0.1mm segments [50]) as of yet not being applied to electronics fabrication.

3 Spray and Etch Working Principles

3.1 Direct Etching

The core innovation of Spray and Etch is the paired method of: 1) hand-held spraying active materials, such as a conductive copper ink [30]; and 2) placing the substrate in an unmodified laser cutter, and use standard laser etching software to etch away active material. We term this combined process as **Direct Etching**. We primarily explore it's use for the creation of electroluminescent displays. This combined fabrication approach moves significantly beyond prior masked sprayed interfaces [52] or laser cut circuits [17] in both the resolution of output device and simplicity of workflow.



Figure 2: Spray and Etch Equipment: (A) we use Lumilor [30] EL materials, hand-sprayed through an airbrush with appropriate PPE. To produce high resolution electronic traces we use (B) an unmodified Trotec 100 Speedy laser etcher.

3.1.1 Spraying: We implement spray deposition through a hand-held airbrush or rattle can (see Figure 2) [21, 52]. This adheres to a process for *cohesive spraying*: spraying in a continuous coat without the need for precise positioning of the airbrush such that material formation is purely programmatically determined through the subsequent laser etching. Spraying allows for: (1) relatively low-skill threshold use; (2) additive deposition in a way that comparative methods do not (e.g. hydroprinting [16], screen printing [37]); (3) application of thin even coats of material well-suited to EL device fabrication; (4) application to non-planar topographies; and (5) affordability in fabrication tools. From our experience and related work [20, 25, 29, 52], non-professional users can quickly master spraying after a few exploratory attempts. We used an Iwata Eclipse HP-CS [23], and samples were left to dry 15 minutes after spraying before subsequent steps were carried out.

Prior work relies on lower resolution to accommodate for variances resulting from hand-deposition. We mitigate for this variance by specifically applying each layer of material in multiple thin coats to modulate thickness with the airbrush held at a consistent 20cm range from the substrate. Within our experimental work we found that multiple thin coats mitigated potential issues with inconsistent layer thicknesses.



Figure 3: Direct etching for electroluminescent (EL) cells: (A) Handheld cohesive spraying to deposit conductive material; (B) direct etching with a laser cutter for high-resolution patterning; (C) EL layers are applied for a functional EL cell (Figure 1D).

3.1.2 Direct Etching: Direct etching is implemented by taking a substrate with sprayed on active materials, that are at least touch dry (5-15 minutes drying time), and placing it into a laser cutter. The target patterns were converted into binary masks, with white indicating preserved material areas and black indicating laser ablation, which were directly loaded to the laser cutter as SVGs. This process is sufficiently powerful and precise to create electrical isolation of strands allowing the formation of precise and organic conductive traces. Replacing traditional additive manufacturing masking methods [29, 52] with a combined additive and subtractive process reduces the burden on the maker and supports output devices with resolutions that would otherwise not be possible. For the EL spraying (see Figure Figure 3), we use a ZnS-based [30] EL capacitor layer structure, with paired electrodes of conductive copper based ink and a Poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) solution for the Transparent Conductive Electrode (TCE) [52]. We did not observe significant warpage or substrate heat damage from thermal accumulation in any of our samples from the laser ablation process

We identify that lateral shaping of electrodes remains one of the primary challenges to creating high resolution displays [21, 37, 52]. Masking requires experience and dexterity to create masks, place masks, and remove them without damaging paint. Spray and Etch provides a **reliable** alternative, especially given that, as fabricated displays get more complex, the likelihood of error also increases. Spray and Etch is **rapid** with the laser cutter we used[2], etching at up to 430cm/s. For example, processing a highly complex pattern on a 10cm×10cm sample with approximately 50% material removal takes between 4–5 minutes, juxtaposed against traditional methods where placement of masks is not only tedious but also requires full curing of base layers to avoid damage. Lastly, Spray and Etch is also inherently **scalable**, enabling replicability and production of multiple identical patterns for testing, distribution or development. This is especially useful when moving from high-fidelity prototyping to low quantity production runs [22]. Spray and Etch also provides key improvements to final output device fidelity. The Spray and Etch process has **high accuracy** producing devices consistently at a resolution of 0.4mm, a resolution not possible through masking (see Figure 1). Further, the etching of sprayed material provides a **smooth edge profile**, avoiding the spray build up of edge masking [21] while maintaining resolution and reducing potential faults.

[2]https://www.troteclaser.com/en-gb/laser-machines/laser-engravers-speedy-series; Last accessed March 2026

3.1.3 Implementing Etching on a Laser Cutter. We conducted a preliminary investigation of the recorded "Hackerspaces" in the UK[3], and found that approximately 33 of the 48 recorded spaces (68%) had a laser engraver. More than half of the 33, list models that use CO_2 laser sources. Although this older technology has drawbacks compared with more modern laser etching machines, such as fiber etching, they maintain a low-price point and therefore widespread prevalence. As such we use a small CO_2 laser, the Trotec Speedy 100 laser cutter machine [50] in this work. Our airbrushing set-up is identical to that used in Sprayable User Interfaces [52], with the exception that we replaced the dielectric with clear lacquer for reliability and implementation speed. To ensure appropriate health and safety measures we carried out extended risk assessment. We primarily identified the major risk, that would not be handled by standard safety set-up such as laser cutter ventilator, as being whether the materials being etched contained any chlorides which we ruled out through MSDS sheets [32]. Standard PPE (respirator, nitrile gloves, ventilation) is otherwise necessary.

Laser etching within a laser cutter is functionally carried out as a very rapid, low power function of laser cutting. We used the Trotec Speedy 100 (Figure 2) with between 70% and 100% power [34]. We also explored other laser cutting machines, including the H2D Bambu machine, with positive results.

3.2 Depth-selective Laser Etching

Through extended scoping experiments we develop an extension of direct etching: **"depth-selective laser etching"**. This approach involves optimizing the ablative removal power of the laser so that a material can be etched at the top of a layered sandwich structure of deposited materials without damaging materials beneath. For example, etching the TCE at the top of an EL structure (Figure 4). While this method is delicate as it involves removing material layers that are as thin as 0.0127mm [31], it is very powerful in unlocking a broad space of different potential electronic structures within personal fabrication such as a passive matrix structure. This process is non-trivial to implement, to ensure that the etching can provide electrical separation of the top material while not damaging lower materials. This process relies on precision in both the position of the substrate within the laser cutter, reliability of the laser cutter's regular functionality and visually checking of outputs. The physical profile of the etching channel (see Figure 5A) must also be taken into account when accommodating for electrical behavior. For example this profile has important implications when avoiding under-etching, as the channel's surface width does not accurately reflect the remaining material at the base.

3.3 Multicolour Display Working Principle

We further identify that depth-selective laser etching can unlock the personal fabrication of dynamic multicolour displays. Multicolour displays are only possible due to the high resolution, streamlining for the fabrication process and lack of masking enabled by Spray and Etch. Starting with direct laser etching to shape a base electrode (see Figure 6A), we then cohesively add three different coloured EL phosphors and dielectric materials, allowing each layer to obscure the others. We then implement depth-selective laser etching to

[3]https://wiki.hackerspaces.org/United_Kingdom; Last accessed March 2026

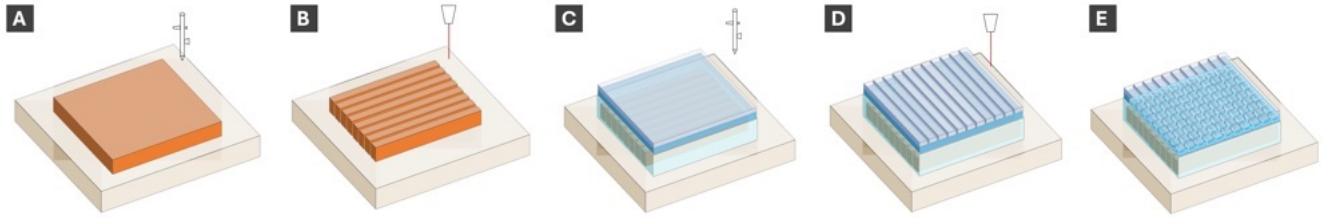


Figure 4: The Spray and Etch basic pipeline for maskingless high resolution EL display fabrication. First (A) A cohesive base layer of copper is sprayed onto the object, which can (B) be shaped into base electrodes using laser etching. (C) The dielectric, EL and TCE layers are sprayed onto the etched base in cohesive layers. (D) Finally, patterns can be selectively etched into the top electrodes enabling a passive matrix with (E) individually addressable pixels.

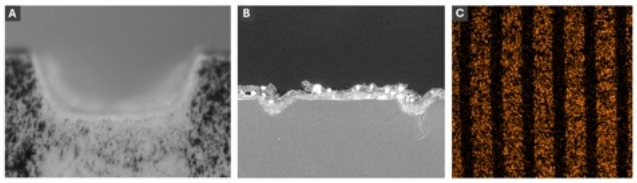


Figure 5: Analyses of copper etching: (A) Profile microscope image [11] of a laser etched acrylic channel; (B) SEM image of matrix structure, showing limited protruding lip relative to contact masking [21]; (C) BSE analysis image of 0.2mm etched copper lines showing clear separation between connection lines and minimal material damage.

remove the phosphor in different areas to reveal a custom colour at any given location. Lastly the TCE is applied and etched to form a structured top electrode. By selectively etching different layers of electroluminescent phosphor, we are able to produce sets of 3 unique coloured pixels between two single cohesively sprayed electrodes that can be individually addressed. By varying intensity of current, similar to LCD RGB displays, we can dynamically produce a range of colour output. This visual merging of colours is only possible with a sufficiently high resolution of display pixels. Spray and Etch provides a reduction in the complexity of pixel placement, failure rates associated with multilayer structures and the ease with which a maker can carry out the fabrication process. This approach would not be possible through masking [52], screen printing [37] or thermoplastic layering [21].

3.3.1 Calibration Routine via Visual Inspection: Due to variations between different laser etching machines, tuning the laser etching parameters is crucial for achieving high-resolution displays. Achieving "depth-selective" etching in particular requires precise tuning of laser power and speed to target the correct depth with high accuracy [31]. We propose a manual calibration where a user adds a layer of inactive acrylic paint with a bright colour, below the TCE, which will in turn function as an additional dielectric. Experimental work showed this had minimal impact on luminescence. Through this, a user can easily perform an optical inspection to see when a top layer has been cut through and a bottom layer has been untouched. Once a calibration has been performed on a particular substrate, settings can be saved and reused, resulting the short calibration (approximately 30 minutes) only having to be repeated when the material stack, substrate, laser cutter, or spraying condition changes, akin to z-calibration in a 3D printer.

3.3.2 Multicolour Calibration . We extend the depth-selective calibration routine for these complex multilayered structures. For the core depth selective etching step, we have a stack of four, white in appearance, thin layers that must be differentially etched (EL phosphors all appear white to the naked eye). Extending the previous calibration routine, we replace the dielectric layers with non-conductive acrylic paints of different colours. This creates visual feedback for laser processing without causing significant deviation in the color display of the final product (Figure 7). If the dielectric colors are chosen to match the EL color in the layer directly above, the color revealed after etching reveals the color of the currently exposed electroluminescent pigment. This greatly increases the operability of this process in making dynamic color displays.

3.4 Direct-etching on Non-planar Surfaces

Spray and Etch can be applied to flexible substrates in the same way as PrintScreen [37] with the notable exception that substrate materials must be temperature resistant so as not to sustain damage from the etching process (e.g. Figure 1 shows the direct etched EL demo on a flexible substrate). Spray and Etch can be applied to non-planar surfaces with no zero-crossings in the structures.

The z-axis of a high-powered laser cutter is typically not dynamic while the laser cutter is working. To implement Spray and Etch on an uneven substrate, a maker must (1) ensure the substrate fits within the laser cutter within the maximum depth of the laser cutter's plate; (2) ensure that the difference between the highest and lowest points of the uneven surface must be less than the maximum focal range of the laser cutter (11cm maximum for the Trotec we use, but with 2cm for high resolution functionality [50]).

When on the extremes of the focal range, the laser engraving machine will be in a defocused state with a reduced etching capability and reduced precision that must be accounted for through increased power and careful positioning [40]. We propose transforming the surface depth information into laser setting parameters, which we do manually. Due to the profile of material removal from

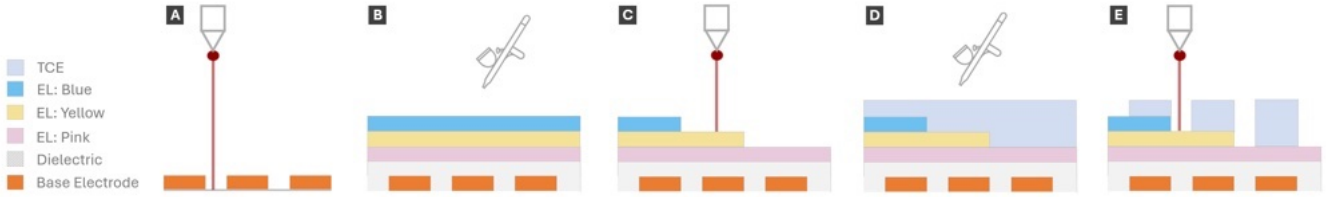


Figure 6: Through Spray and Etch, makers can create high resolution multicolour pixelled structures. (A) First, a layer of copper is sprayed and directly etched to produce base electrodes; (B) A dielectric and three different colours of EL phosphor are layered on cohesively (EL1:blue, EL2:yellow, EL3:pink); (C) layers are selectively etched to reveal a single colour as the top colour which will be the colour shown in the pixel, enabling colour selection on a programmatic level through the etching; (D) the TCE is layered and then (E) etched into layeral electrodes producing adjacent pixels of different colours that in line with LCD technology can be lit at different intensities to produce a continuum of colours.

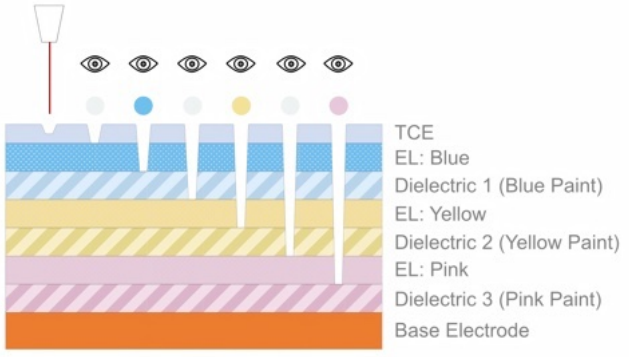


Figure 7: Spray and Etch *Multicolour calibration routine* for implementing visual feedback on etching depth. Different EL materials that luminesce with various colours are identical in physical properties, showing as a white material. Rather than introduce additional equipment, we add dielectric layers of appropriately coloured acrylic paint so that the maker can observe tolerances for etching with too high power.

the laser etching's path (see Figure 5), etching at an angled surface requires broader channels between conductive layers due to increased overhang of materials on the edge of etched channels.

4 Performance Characterisations

We present eight performance characterisations of Spray and Etch. Tests 1–4 evaluate the efficacy and accuracy of direct laser etching on copper-based electrodes and on PEDOT:PSS TCEs. Tests 5–7 explore the fabrication of dynamic multicolour EL displays. Finally, Test 8 addresses the peformance of etching on a sloped surface.

4.1 Test 1: Setting Parameter's Impact on Base-layer Etching

Summary: We explore how the three key laser-etching input factors: *power*, *running speed* and *offset from the focal point* interplay when etching a sprayed copper base-layer to parameterise *direct laser etching*. The test showed that at the focal point, material could be etched at 30% max power and 60% max speed with increasing values needed further from the focal point.

Comparison samples: We prepared a test sheet of 500 discrete samples for the analysis. The sheet was created with a stencil to produce $7mm \times 7mm$ squares in a series of rows and columns, which were then sprayed with a cohesive copper base layer [30]. These sheets were produced through cohesive batch-coated substrates with 2 thin coats of material, reducing accumulation inconsistencies from starting and stopping spraying. Each sample was processed by etching a single 9mm line bisecting the sample, with varying power, speed and offset. Each sample was etched with a separate combination of distance from the focal point (0mm–20mm, with 5mm steps), running speed (10%–100% with a step length of 10%) and power (10%–100% with a step length of 10%). Each test resulted in a binary classification on the success of electrical separation. This was verified using a handheld multimeter.

Results and analysis: Test 1 showed that the offset from the focal point had a significant impact on etching (Figure 8, top), with complete etching being achieved across a wide range of powers and running speeds when at 0mm offset, while requiring a combination of high power and slow speeds at 20mm offset. The offset from the focal point has a clear impact on etching performance, the copper was fully etched 71% of the time at 0 mm offset, while only 12% of the time at 20 mm offset. The graphs also show that at 0 mm offset from the focal point, the copper base layer can be fully etched at as low as 30% max power and 60% max speed. However, as the focal point is moved back, higher power and slower running speeds are required to ensure the base layer is completely etched. Even at 20 mm offset from the focal point, the 10% max speed setting is able to fully etch the base layer at as low as 40% max speed.

4.2 Test 2: Setting Parameter's Impact on Depth-selective Etching

Summary: We explore parameters enabling accurate depth-selective laser etching. We look at *power*, *running speed* and *offset from the focal point* when etching a flat TCE (PEDOT:PSS-based [30]) layer as the top part of a three-part capacitor layer structure of copper, dielectric and TCE. It showed that a maximum of 2%

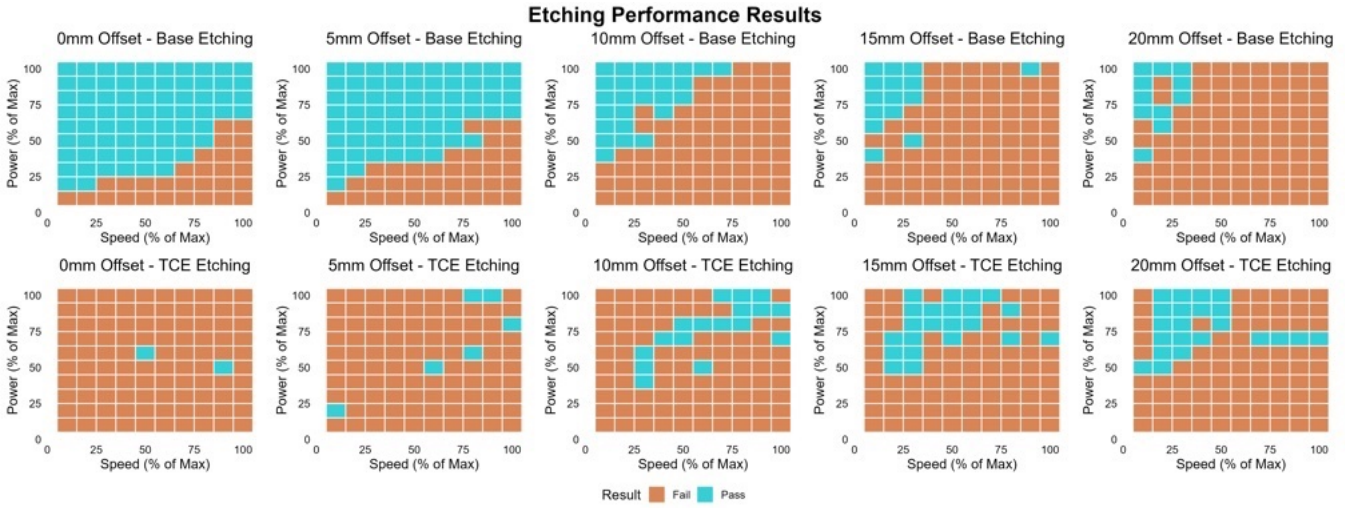


Figure 8: (Tests 1, 2): Shown are the test results showing the factors of *Power*, *Running Speed* and *Offsets from the focal point*, in both direct etching of the copper base layer and depth-selective etching of the TCE top layer of a capacitor structure.

power was able to etch the TCE while not damaging the copper, but additional focal point offset gave a greater functional range (22%).

Comparison samples: As with, Test 1, we prepared 500 discrete samples on a sheet. The sheet was masked with rows and columns, and sprayed with copper, to create the base layer of the $7mm \times 7mm$ samples. After this, the row masking was removed, before the sheet was sprayed with dielectric, to create continuous columns of insulation. Finally, the rows we re-masked and the samples were sprayed with the TCE to create 500 capacitor structures on an offset, such that the conductivity of the copper and TCE could be checked with multimeter probes. Electrical isolation was verified using a handheld multimeter before etching. Laser etching input parameters were tested with a distance from the focal point (0mm–20mm, with 5mm steps), running speed (10%–100% with a step length of 10%) and power (10%–100% with a step length of 10%). The validity of the sample was checked after etching. In this sample we explored the parameters within which the TCE could be etched without breaking through the dielectric and damaging the base copper. This involved checking the resistivity across the two halves of the etched TCE, followed by the resistivity across the two halves of the base copper layer. For a sample to pass, it must have both no connectivity across the TCE as well as connectivity across the copper base layer.

Results and analysis: The results for Test 2 are shown in Figure 8 (bottom), and should be directly compared with Test 1, indicating that the strength of the fabrication process within this test was consistently lower than Test 1. Test 2 demonstrated the challenges in depth-selective etching at small offsets from the focal point, and the wider tolerance when the offset is increased. Unlike Test 1, the performance improved with focal point offset, with only 2% of power and speed combinations able to successfully etch the TCE, without damaging the copper at 0 mm offset, while 22% were successful at 20 mm offset. The graphs also show how achieving success in depth-selective etching at 10% speed is very challenging.

4.3 Test 3: Impact of Focal Point Offset on Etching Resolution

Summary: Tests 1 and 2 showed how changing the offset from the focal point increased the power of etching. To understand the impact that the focal point has on etching width, we conducted a visual inspection test on copper samples. The test showed how the width of the etched line increased with offset from the focal point.

Comparison samples: We sprayed a plastic sheet with a cohesive layer of copper to create a single continuous surface from which we prepared our sample. We then etched five lines, each 10 mm long, in a horizontal line across a section of the sheet. Each line is etched at 80% max power and 100% max speed. These settings provided high energy without significant damage to the plastic. The five lines were each at different offsets from the focal point, from 0 mm to 20 mm. The line was then photographed under a microscope and visually inspected.

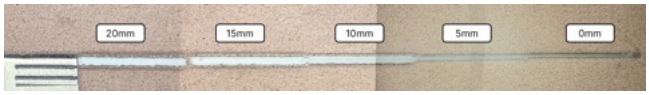


Figure 9: Test 3 explores the impact of offset from the focal point when etching copper, with offset decreasing from left (20mm) to right (0mm).

Results and analysis: The results are shown in Figure 9, which demonstrates the impact of offset from the focal point on etching resolution. The line etched at 20 mm offset has a width of approximately 0.8mm with decreasing offsets corresponding to widths of 0.69mm (15mm offset), 0.55mm (10mm offset), 0.36mm (5mm offset) and 0.22mm (0mm offset). The 20 mm offset line also had a much rougher edge compared to the lines with lower offset.

4.4 Test 4: Minimum Resolution

Summary: We investigated the minimum functional distance between etched lines. Understanding this value allows us to calculate the smallest display resolution possible via Spray and Etch. The results show a minimum reliable line width of 0.2mm.

Comparison samples: We created four squares on a plastic sheet, then sprayed on a cohesive layer of copper paint. Each of these samples was then etched with a series of horizontal lines, running parallel across the width of the sample. The distance between the lines were 1.5mm, 0.6mm, 0.2mm and 0.1mm. Each sample was visually inspected under a microscope and was also checked for electrical connection, using a multimeter. Samples were deemed intact if they were conductive along the etched lines and if they were also not conductive between parallel lines.

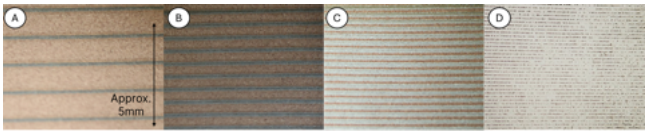


Figure 10: Test 4 explores the impact of the distance between etched lines on the resulting copper path. Four gaps were tested, (A) 1.5mm, (B) 0.6mm, (C) 0.2mm and (D) 0.1mm. The consistency of copper channels can be seen up to 0.2mm, while below this they begin to break apart.

Results and analysis: Test 4 demonstrated that the minimum reliable control line that can be etched is 0.2mm, resulting in a minimum producable rectangular pixel of 0.04mm^2. The results for the four samples are shown in Figure 10. For all the samples except the 0.1mm spacing, the tests showed electrical separation between rows, as well as electrical connectivity along the rows. However, as can be seen in Figure 10D, at 0.1mm spacing, the copper began to break down and connectivity along the rows was lost.

4.5 Test 5: Colour Range

Summary: To evaluate the effectiveness of selective etching within a multilayered EL structure, we created several coloured samples and visually inspected them. The test showed that Blue EL was overly prevalent, however all samples had some colour variation.

Comparison samples: Six samples were made using Yellow, Pink and Blue Luminor EL paint. Each sample had a different order of Yellow, Pink and Blue Paint, and all samples had the same conductive base layer and TCE. Before the TCE was applied, the sample was selectively etched, to create three segments (method shown in Figure 6). The first with no etching, the second with the top layer etched to reveal the middle layer and the third with the top and middle layer etched to reveal to bottom layer. The samples were visually inspected and photographed under the same conditions.

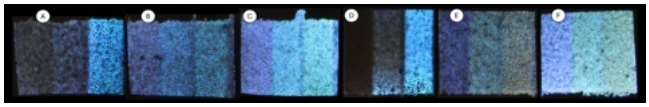


Figure 11: (Test 5) Multicolour samples after being etched, under AC power. Each image shows an unetched layer (Left), top layer etched (Mid) and top and middle layer etched (Right). EL paints; Blue (B), Pink (P) and Yellow (Y); were sprayed in six different orders: A) YPB, B) YBP, C) PBY, D) PYB, E) BYP, F) BPY.

Results and analysis: This test revealed that when trying to selectively etch EL layers without visual feedback, the results are inconsistent and dominated by the Blue EL (see Figure 11). Although there is some variations in brightness and colour across the etched layers, all the samples are dominated by the blue EL. Both samples with the Blue EL on the bottom, Figure 11A and D, were the least bright, while samples with Blue EL at the top, Figure 11E and F, had wider ranges of colours visible.

4.6 Test 6: Colour Range with Visual Guides

Summary: We evaluated the Multicolour calibration visual feedback approach (method shown in Figure 7), which utilises coloured dielectic layers between each layer of EL, to provide a visual confirmation when etching that the correct depth has been reached. This test showed a broad colour gamut, with overall sample brightness being lower as a result of thicker layers.

Comparison samples: As with Test 5, six samples with different orders of Blue, Pink and Yellow EL were created. However, above each layer of EL was a corresponding coloured dielectic layer. The samples were etched into three segments, to reveal the three different EL layers. The samples were visually inspected and photographed under the same conditions as Test 5.

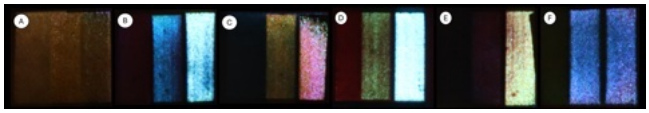


Figure 12: (Test 6) Samples after etching with added visual feedback layers during spraying, shown illuminated under AC power. Each image shows the unetched layer (left), etched to show the middle feedback color (center), and etched to show the bottom feedback colour (right). Three EL paints; blue (B), pink (P), and yellow (Y); were sprayed in six different orders: A) YPB, B) PBY, C) BYP, D) PYB, E) BPY, F) YBP.

Results and analysis: A distinct range of colours can be produced from a set of cohesively sprayed layers, by etching away select layers while using the visual confirmation (see Figure 12). However, the brightness of the samples is significantly reduced , suggesting either impacts on overetching or reduced capacitance from maximising layers within an 11 layer structure. Notably, unlike in Test 5, there were several segments with no luminance visible in the tests. There were also inconsistencies, with samples such as

Figure 12F showing blue at both the mid and bottom layers and the blue sample not visible at all on Figure 12C and E.

4.7 Test 7: Effect of Material Colour on Laser Engraving

Summary: We explore the impact of surface colour on key laser etching parameters in order to validate the mutlicolour calibration visual feedback approach presented above, under different power, running speed and focal point offset. It showed there was no notable difference between etching effect on different coloured acrylics.

Comparison samples: We used four different coloured sheets of acrylic paint (Red, Green, Purple, Black) as the samples. Each sample was etched with a line, with a different combination of power, running speed and focal length offset, to create 500 different combinations (using the same variable settings from Tests 1 and 2). Each sample was then visually inspected to check if the laser had etched through the depth of the sheet. Unlike Tests 1 and 2, the samples were not conductive, so it was not possible to check for conductivity across the edge.

Result: Our results showed that between the Red, Green, Purple and Black sheets there were no differences in etching performance. All four of the sheets had 252 samples which were fully cut. This shows that between the coloured sheets tested, there isn't a noticeable impact of colour on etching performance.

4.8 Test 8: Effect of Depth on Base Layer Etching

Summary: We tested the effect of depth on base layer etching under different power settings, by etching the sample on a 30° inclined plane placed on the base of the laser cutting areas. These results showed that within 20mm of the focal point, material can be effectively removed by modulating power.

Comparison samples: Copper paint was sprayed on the acrylic plate and allowed to dry, and uniform conductivity was confirmed across the sample. 200 discrete samples of 5mm × 9mm at 1mm intervals apart were etched, in a 10 columns and 20 rows arrangement. The sample was fixed to two additional acrylic plates, to set it at 30° from the horizontal plane, with the columns set at an angle.

The sample was set at a height so that the laser focal point was inline with the highest edge of the sample. A line was etched down the centre of each column, passing through all 20 rows, in the direction of descending the inclined plane. Each column was etched with different laser energy settings (10%–100%, step size of 10%). Then the resistivity at both sides of the etched line of each engraved sample was tested for conductivity. For each column, we recorded the lowest sample depth at which it could be fully separated for that given laser energy setting.

Result: The maximum effective depth that base layer etching can be achieved on this laser engraver is 20mm, and the relationship between laser power and maximum etching depth is approximately linear (see Figure 13). For the 100% power column, the lowest depth at which the sample could be fully separated was 20mm, which demonstrates a maximum effective etching depth of this laser engraving machine of 20mm. For the remaining nine columns, the effective etching depth gradually decreases with decreasing energy,

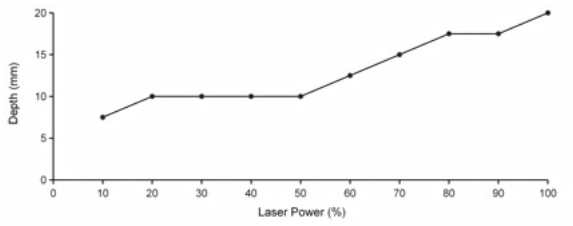


Figure 13: (Test 8) The relationship between laser power and the maximum depth at which the copper sprayed base layer could be fully separated via the etching.

in an approximately linear relationship. The TCE is significantly thinner than the base layer and takes less power to etch, so we suggest that the trend in Figure 13 is likely appropriate to extrapolate.

5 Technical Demonstrations

We show Spray and Etch through five technical demonstrations.

5.1 Demonstration 1: High Resolution Passive Matrix Display

While most display fabrication work explores segmented displays [19], pixelated structures support dynamic, complex information display, including real-time video output. Using depth-selective laser etching, we produce a high resolution passive matrix display through direct etching of a copper base layer for horizontal electrodes, cohesive layering of EL phosphor and dielectric and then depth selective etching of the TCE top coat to produce vertical electrodes (see Figure 4). We present an 32×32 pixel display with channel widths of 0.1mm and pixel sizes of 0.4mm, giving a resolution of 50.8PPI. This can be compared to the smallest reported personally fabricated EL displays in HCI, with 16 PPI [21] and 30 PPI [37]. It can show images and video with a refresh rate of 0.1 seconds (display update interval). The process has a maximum estimated PPI of 127, currently limited by the pre-fabricated dimensions of the anisotropic tape that we use for circuit attachment.

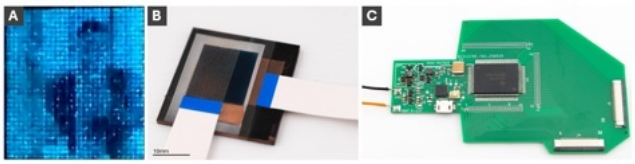


Figure 14: Infrastructure for high resolution EL passive matrix display demonstration: A) still image from the display showing the video of Rick Astley's "Never going to give you up" (see video figure) at a video output rate of 60 frames/second; B) passive matrix showing the use of anisotropic tape to connect electrodes; C) EL Matrix driver, developed based on Krasnow's work [28].

This demonstration embodies the core innovation of this work, a step change in the resolution that can be attained. Due to the miniaturization of the electronic structures, we can't use electrode attachment methods see in related work so instead, we used anisotropic display tape[4] to connect electrodes to the control circuit. We developed an updated control board, largely built on Ben Krasnow's open-access control circuit [28] to drive the EL cells Figure 14. Beyond updating components, these modifications allowed for direct connection of anisotropic tape to the board. The tape was then connected to the etched copper electrodes through a pressure fit with miniature clamps. The PCB schematic is made open-access in supplementary materials, in line with Ben Krasnow's original open access PCB. Using the results from the experiments, the matrix and other functional samples were produced with the settings of 100% rate and 80% power for direct etching base copper layer and 100% rate and 40% power for depth selective etching of the TCE. The matrix was produced using a blue EL phosphor [30] and with two layers of clear lacquer as dielectric to reduce risk of short circuit.

5.2 Demonstration 2: Custom Signage and Logos

We produce a range of custom signs and logos to demonstrate both the high resolution of just the depth selective processes in isolation, the geometries that can be achieved without masking and the speed at which our approach can produce high resolution EL segments programmatically, with a common-place unmodified laser cutter. Inspired by PrintScreen [37], we show an EL tree pattern, demonstrating islands and areas that would be almost impossible to mask by hand at this scale, even for a specialist user (see Figure 15).

Each of the base layers for these patterns took under 2 minutes to produce using spraying and etching. If we compare this to the alternative of masking [9, 29, 52] or 3D printing base electrodes [21], this is an order of magnitude faster and requires limited skill beyond spraying.

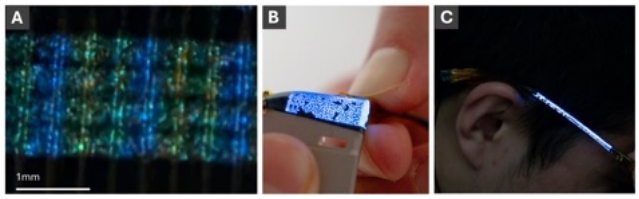


Figure 15: Demonstrations of Spray and Etch electroluminescent surfaces. A) a multicolour pixillated display, with addressable pixels, shown under a Kern OZL 961 Stereo Microscope at 4.5x magnification; B) an interactive segment added to a Nintendo Switch controller demonstrating a non-planar display; C) a custom interactive surface used to augment glasses with luminescent text.

5.3 Demonstration 3: Multicolour Pixels

We produced a prototype passive matrix with different colour pixels, shown in Figure 15 under a Kern OZL 961 Stereo Microscope. These pixels are individually addressable and based on an LCD structure of having contrasting colours adjacent to enable light-bleed to produce multicolour displays. This display has the same scale as the full passive matrix: 50.8PPI or 0.4mm pixels. However, as multicolour is achieved by 3 adjacent pixels, functionally, each fully addressable set of pixels fills a dimension of 0.4mm by 1.4mm. This demonstration was produced by spraying a copper base layer, direct etching horizontal electrodes, then alternating spraying of dielectric, blue EL phosphor, dielectric, yellow EL phosphor, dielectric, pink EL phosphor. Depth selective etching was then applied to remove 0, 1 or 2 phosphor layers to uncover each colour in turn, and therefore programmably producing a multicolour display (method shown in Figure 6). Finally the TCE was added and depth selectively etched to produce vertical electrodes. This demonstration is a proof of concept over technical feasibility of this approach for adjacent multicoloured pixels. However, when individual patterns were applied to the array, the colour bleed renders colour variation as minimally distinguishable to the human eye. We propose further investigations to enhance difference in colour variation to minimise layer thicknesses and further optimise depth selective etching.

5.4 Demonstration 4: Interactive Nail Display

Extending our technical demonstrations, we use the Spray and Etch process to explore applications, of which implementations at this resolution have been sought after within prior HCI work. We explore the creation of nail displays as a wearable interface (Figure 1). By using false nails that can be placed within the laser cutter, the Spray and Etch technique could unlock the fingernail as an interaction space allowing for fine enough resolution to provide pixellated displays building on previous work within HCI [10, 15]. This application in particular highlights the capabilities of the etching process on a non-planar surface within an appropriate focal-point range.

5.5 Demonstration 5: Augmentative Interactive Surfaces

Further demonstrations explore the use of wearables (glasses) and controllers (a game controller) to add interactive surfaces to existing objects (see Figure 1, Figure 15). These further demonstrate the use of Spray and Etch on non-planar surface, demonstrating the scope of use on gently curved surfaces to remain within focal point range, and choosing substrates that are resistant to short-term heat bursts.

6 Discussion

6.1 Limitations

Heat damage from low laser speeds. Through experimental results, we observed that while etching efficiency is a direct function of power and speed, lower speeds can lead to high heat accumulation which can damage substrates and active materials. In particular, in the context of depth-selective etching, highspeeds must be maintained so as not to damage layered structures. Further, increasing the focal point offset dampens the engraving energy transferred to the material, which widens the power and speed range over which successful depth-selective etching can be achieved.

Limitations in fabrication process. As evidenced by the fabricated outputs and performance characterisations, the process presented had a high reliability while still relying on unaltered fabrication

[4] https://thepihut.com/products/3m-z-axis-conductive-tape-9703-2x6-50mm-x-150mm-strip; Last accessed March 2026

hardware. However, due to the visual alignment process of the substrate in the laser cutter, especially during extended alternations between spraying and laser cutting, accuracy was limited to 0.1mm variation. We propose that in future work computer vision could support substrate placement.

Non-planar and multicolour constraints. Drawing from the performance evaluations and technical demonstrations, we conclude that non-planar applications are only supported on gently curved, non-coplanar surfaces. We were further limited in successfully exploring non-planar surface etching and dynamic multicolour etching together. In Spray and Etch's current form with the variability of hand-held spraying and the limitations of laser focal points, our explorations demonstrated that depth-selective etching is too refined to do for non-planar application with multicolour functionality. We propose an extension, moving beyond the commonplace CO2 laser cutters frequently found in maker spaces and propose extending this process with fibre etching which offer potentially higher efficiency and precision when processing copper materials [48].

Colour limitations. Through technical evaluations and informal experiments, we have been able to scope some of the challenges around programmatically determining colour EL display segments. The primary limitation is the colour gamut and brightness of different EL materials. As shown in Figures 11 and 12, certain colours, in particular blues and aqua provide strong bright colours. While yellow, violet or orange are far less bright. In addition, we are limited to the range of 'neon' colours for what is possible through electroluminescent phosphors.

6.2 Future Work

Refinement of Spray and Etch. When carrying out depth-selective etching, over-etching can cause damage to sublayers. We propose further research into increasing tolerances by adding "protective" laser-blocking layers, which can limit the etching power of the laser, inspired by Dobelis *et al.*'s work [12]. We also speculate, from our experimental results, that with three layers of both dielectric and EL, the electrical field is reduced, causing a performance drop and propose further investigations into material and thickness tolerances on functionality - further exploration of dielectric materials could improve this functionality. Similarly, explorations over ranges of substrate would enable exploration of this process into deformable structures [6] including the necessary material explorations such as stress analyses. We propose the key to unlocking the full gamut of multicolour high-resolution displays is through the integration of *tolerance sensing* through microscopy, computer vision and active sensing of structures. Further hardware variations should be explored such as fibre etching, which likely will have higher performance outcomes juxtaposed against prevalence within makerspaces. We also identify that high levels of ghosting from the passive matrix and variability through electrode connections could be mitigated through further development of responsive control.

Explorations of Spray and Etch in-situ: We propose that the next step for this work is a user study-based exploration of the Spray and Etch process by novice users and the ease of its adoption within the context of personal fabrication. While the distinct processes such as EL spraying [20] have been explored, the learnability of the process and pay off between resolution of output artifacts against user skill-sets would provide further depth on this project.

Technologies beyond EL. The rapid fabrication of high-resolution electronic structures demonstrated in this work should be explored in the context of other functional structures to enable digital interaction. We propose explorations into novel sensing structures, as well as transparent conductive electrodes for augmenting day-to-day objects with touch through electrotactile feedback. We further suggest integration of electronics fabrication approaches such as Printegrated Circuits [8] and Solderless PCB [54] using state-of-the-art existing fabrication equipment in the form of the H2D 3D printer [2]. This process is a step-change in resolution for further electronics fabrication.

6.3 Vision

Automated Spray and Etch: The reliance on hand-held spraying provides a process accessible to non-specialists, however it adds variability to thickness and uniformity of different layers, even over a single sample. This not only reduces reliability but increases the threshold for user domain knowledge raising the barrier to access by non-specialists [3]. Similarly, laser cutters will often have non-standardised power and speed settings [42, 44], increasing the emphasis on calibration through a user's experience. While we provide calibration procedures in this work, we propose that future looking work explores automation of processes. Automation also opens the way to decentralisation of design, in a manner akin to 3D printing where design and production are uncoupled so that makers can access online libraries of designs to implement without the prohibitive need to develop bespoke design skills [19].

7 Conclusion

Spray and Etch is a personal fabrication process for high resolution electroluminescent displays that represents a step change in the creation of interactive devices, enabling high-resolution displays far beyond what is possible through existing additive methods. Our process uses unmodified existing tools and equipment common to makerspaces, making it accessible to a wide audience. We provide an overview of the Spray and Etch method and a series of characterisation experiments exploring this approach. We believe Spray and Etch will significantly increase the number of users who can prototype and produce their own custom-shaped displays.

Acknowledgments

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