Supporting Prototyping of Novel Interfaces Using Laser Cut Clear Perspex

Aluna Everitt
aluna.everitt@cs.ox.ac.uk
University of Oxford
Oxford, United Kingdom

Miriam Sturdee
m.sturdee@lancaster.ac.uk
Lancaster University
Lancaster, United Kingdom

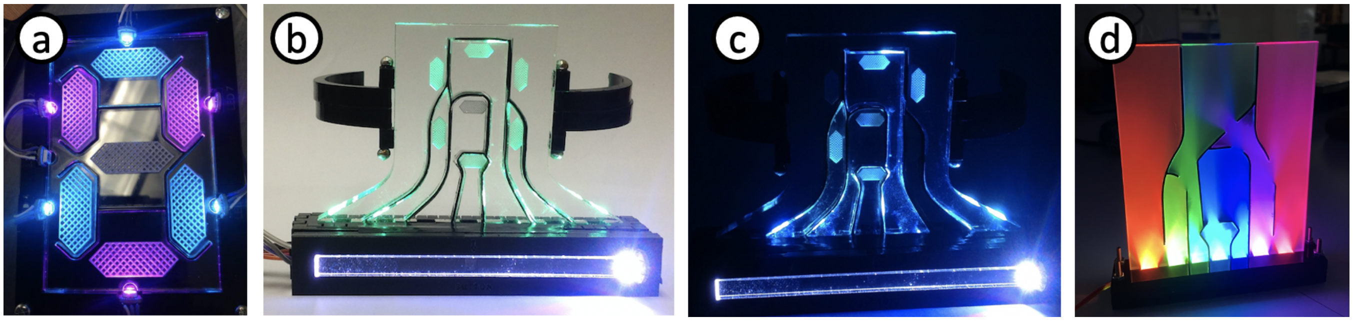

Figure 1: Initial light tests on each etched segment of Perspex to create a display (a); A seven-segment watch display prototype showing number "0" in day light (b); "2" with no ambient light (c); Abstract design of display to explore colour light diffusion (d).

ABSTRACT

Digital fabrication technologies such as laser cutters have been widely used for supporting prototyping of interactive devices as they are able to work with a wide range of materials. However, the majority of laser cut prototype components are often unable to support interaction or visualisation capabilities within themselves (e.g., functionality embedded within the material). Often materials that are laser cut do not have functional properties aside from serving as enclosures for interactive components. Our work explores how optical properties of clear Perspex material can be exploited to support interaction and visualisation capabilities for interface prototyping. Our proposed fabrication approach demonstrates the potential to support the development of novel displays devices that do not require expensive or complex circuitry and electronics. We produce a light-sensitive button and a seven-segment display which are combined into a wearable watch prototype demo. We also discuss design implications and future direction for this work.

CCS CONCEPTS

• **Human-centered computing** → **Interaction devices**.

KEYWORDS

Fabrication, Wearables, Laser Cutting, Prototyping Interfaces

---

ACM Reference Format:
Aluna Everitt and Miriam Sturdee. 2022. Supporting Prototyping of Novel Interfaces Using Laser Cut Clear Perspex. In *Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '22), February 13–16, 2022, Daejeon, Republic of Korea.* ACM, New York, NY, USA, 7 pages. https://doi.org/10.1145/3490149.3505564

1 INTRODUCTION

Digital fabrication technologies, such as 3D printers and laser cutters, are becoming increasingly adopted in a range of settings as they allow users to rapidly and accurately produce functional high-fidelity prototypes [2]. Of these technologies, laser cutters are particularly interesting as they work with a wide range of materials. Nevertheless, using fabrication technologies such as laser cutting can place limitations on prototype capabilities, and therefore impede progress for the design and development of new interactive devices. Such limitations include reproducing complex design methods (e.g., require expert technical knowledge or skills), employing slow manufacturing processes, or using expensive electronics [1, 11]. Additionally, electronic components are commonly situated underneath the surface of a display [17], rely on external projection [5], or are purchased as ready built units and therefore limit customization [4]. Laser cutting is a relatively cheap and accessible method of rapidly producing components, but such components are mainly used as enclosures to house electronic elements rather than having their own functionality. We therefore ask: *could we embed interactivity and visualisation capabilities into laser-cut substrates?* The increasing accessibility and reduced cost of digital fabrication technologies for supporting rapid prototyping also supports a wider audience in research and maker-spaces, thus enabling people to design and develop a new generation of interfaces and devices [13] in applications areas such as wearables [8], data-physicalization [10, 11], and shape-changing displays [6, 19].

We demonstrate how to design and develop simple yet novel tangible interfaces using basic active components and low cost materials to support interaction and visualisation capabilities. Our fabrication method requires three basic electronic components; (1) a photoresistor - also known as a light-dependent resistor (LDR light sensor), (2) an RGB NeoPixel multi colour LED, and (3) an Arduino micro-controller.We embedded the electronic components into enclosures and displays laser cut from clear and black acrylic material. For this work we use Perspex® which is a high end branded acrylic, but other acrylics such as Poly (methyl methacrylate - PMMA) and plexiglass can also be used. Our fabrication approach utilises the material properties of optically clear acrylic (e.g., Perspex) as we manipulate light through laser cutting and etching to support the visualisation and interaction capabilities of our prototype interfaces. First, we explore related work on interface fabrication techniques supporting rapid prototyping, then we describe the design and implementation of elements to produce a functional prototype. The resulting work encompasses:

1. The development of two foundational prototype elements to use with this technique – a light sensitive button switch, and a seven segment display with opaque (black) inserts to helps reduce the number of acrylic sheets used.
2. A wearable proof-of-concept functional watch prototype which combines these elements.

Overall, we contribute an accessible fabrication approach which utilises laser-cut clear acrylic (e.g., Perspex) to prototype interactive interfaces with visualisation capabilities. We also demonstrate how our method can be implemented on a small scale by fabricating an interactive wearable device with a transparent seven-segment display (Figure 1). We believe this work has the potential to influence the rapid prototyping of interactive visual devices for researchers, designers, and makers.

2 RELATED WORK

Fabrication technologies such as 3D printers and laser cutters have revolutionised the way we design and prototype. For this work, we focus on Functional Fabrication as a promising area of research within the domain of prototyping [2, 7]. Digital fabrication can support relatively cheap and accessible methods of rapidly producing prototype components, however, such prototype components are mainly used as enclosures to house electronic elements rather than having their own functionality [12, 20]. Nevertheless, recent work such as LaserFactory [16] enables the creation of functional devices and interfaces using a laser cutter. We present an overview of currently available fabrication techniques and discuss how they have influenced our work in this area. The lower cost of rudimentary 3D printers and desktop laser cutters also means that they can be used outside of research and industry, and adopted more in maker-spaces and even the home environment. Current research in additive manufacturing also has the potential to filter down to novice users in the near future [2].

In terms of 3D printing, Willis et al. [18] describe an approach to 3D printing customizable interactive devices categorised as *Printed Optics*. Each device consists of light pipes that are 3D printed using an optical printer. Light pipes are similar to optical fiber which can be used to guide light from point to point. However, unlike conventional optical fiber, 3D printed light pipes allow arbitrary geometries to be custom designed via software. These functioning devices are designed within a digital 3D modelling editor (e.g., CAD) and realized in a single physical form through optical 3D printing. Active components and optical quality elements are embedded into the device during fabrication. Brockmeyer et al. [3] later advanced this approach by exploring alternative display forms which navigate away from traditional flat displays for interactive applications: *PAPILLON* enables the design of curved display surfaces for information visualisation and input capabilities through 3D modelling. The interactive device is then fabricated through 3D optical printing as a single object. A similar approach to designing and developing interactive devices is also used by Savage et al. [17] who manually embed optical light tubes, electronic sensors or actuation components within the interiors of 3D printed objects. Subtractive processes are implemented through an algorithmic approach to generate space within 3D models for insertion of these active components and electronics which then enable interactivity.

One of the main limitations of 3D printing is that there is need for structural support when fabricating devices with complex geometry. In some cases, device enclosures must be printed in several parts and manually assembled to avoid structural weakness. As a solution, laser cutting can be used to construct similar devices from robust material (e.g., Perspex sheets) within a 2D vector design environment (e.g., Adobe Illustrator). Although manual assembly is still required, with careful design decisions the number of components needed would be reduced compared similar 3D printed devices, particularly when varying prototype scales. Laser cutters can also support interact fabrication of functional mechanical devices [15]. Mueller et al. [14] describe a laser cutting based prototyping approach, LaserOrigami, that fabricates 3D objects significantly faster compared to traditional 3D printing techniques. By stretching and folding material, rather than just placing joints, the need for manual assembly can be reduced.

More recent work utilises laser cut stretchable surfaces with mounted electronic circuits for developing novel interfaces. *LASEC* [8] uses laser cut patterns on a material to support functionality, however, sensing and visualisation capabilities require electronic components situated on top of the laser cut surface. Similarly, *FoldTronics* [19] is another example of an approach where a laser cutter is used to create 3D objects with electronics within foldable honeycomb structures – our work does not focus on stretching interfaces however. Additionally, current state-of-the-art is limited by complex design processes that often require previous experience and knowledge of designing and developing similar styles of complex interfaces. To bridge the complexity gap and encourage more novice designers and makers, we present a new approach to further simplify the fabrication of novel interfaces, reducing the entry barrier for those who do not have knowledge of complex hardware. We purposefully reduce the number of electronics required and keep the design process in a 2D CAD environment rather than 3D modeling.

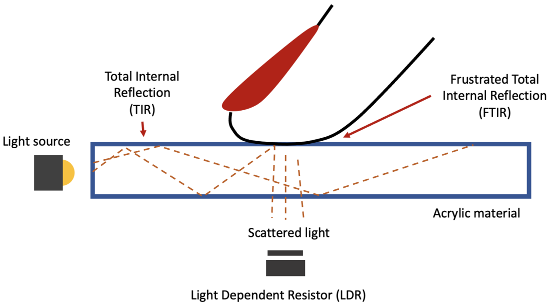

Figure 2: We utilise Frustrated Total Internal Reflection (FTIR) [9] within the Perspex to support interaction capabilities by sensing light wave scattering using a light dependent resistor (LDR).

3 PROTOTYPE ELEMENTS

Our approach utilises Total Internal Reflection (TIR), an optical phenomenon which enables light waves to be reflected *within* a sheet of clear Perspex rather than refracted back out. If material surfaces are smooth and clear, light from one side will be reflected within the acrylic (Figure 2). In order for light to be defused on the surface of the material, a pattern can be lightly etched on the surface of the material to illuminate a segment. For light to be distributed more consistently throughout each segment a crisscross pattern was designed for light diffusion (see Figure 5a). We also utilise Frustrated Total Internal Reflection (FTIR) [9] to support interaction. FTIR is another optical phenomenon where the reflection of light is disrupted when force is applied to the surface of a material, causing light waves to be deflected (Figure 2). From an initial set of material explorations, we created two fundamental prototype elements – an interactive light switch button and a seven-segment display – to enable the construction of a wearable prototype that combined those elements. We developed a simple user input button to demonstrate interaction capabilities achieved with light sensing and expanded on how laser cut devices could be used to display meaningful information without electronics situated behind or on top of the interface surface.

3.1 Light Switch Button

The light switch button (Figure 3) was based on optical sensing that can be achieved through push and pressure application to the surface of the material [9]. By embedding optically clear material into an enclosure fitted with a separate light source, a light switch mechanises was produced. The principle input variable for this button is based on light transmission displacement recorded with a light dependent resistor (LDR). The light switch button is separated into two elements. First, clear Perspex material with light transmitted through it (LED 1) is used to sense user input when pressure is applied to the surface and recorded using an LDR sensor positioned below the material. This is achieved through Frustrated Total Internal Reflection (FTIR) [9] as illustrated in Figure 2. Secondly, a light source (LED 2) is activated when light intensity readings (LDR with a 10k resistor) reach a specified threshold. This threshold is calculated by sampling light intensity behaviour when finger pressure is present on the surface of the material. The colour of LED 2 changes depending on the amount of finger pressure applied to the surface (Figure 3b-c). In total we used 2x LEDs, 1x LDR, and 1x Arduino for processing input and output data. We fabricated an enclosure by laser cutting three pieces of black Perspex. Each of the three layers had specific cavities cut to accommodate three electronic apparatus need for the device.

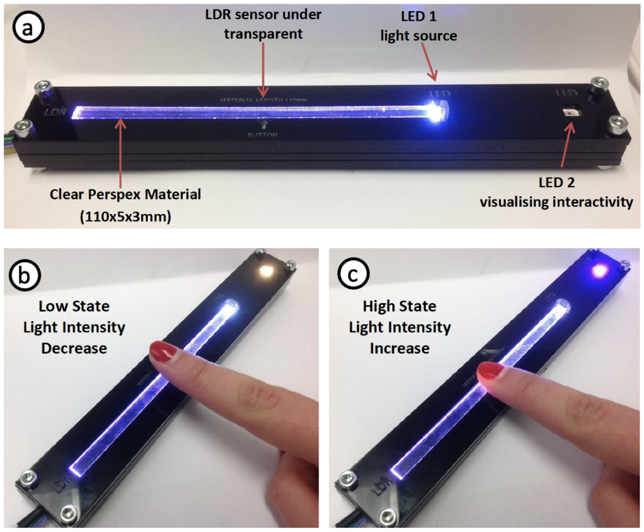

Figure 3: Button light switch when no interaction occurs (a). As pressure on the surface of the material increase, LED 2 changes colour from yellow with light pressure (b), to pink when more finger pressure is applied (c).

3.2 Seven Segment Display

Seven-Segment Displays (SSD) visualise information through individual state transformations of single characters or numerals. Two SSDs were designed and fabricated using laser cut Perspex material. The initial SSD, with seven LEDs around all four sides and a second SSD has light sources situated only at the bottom of the display. Our SSD prototypes were developed in two stages. First, a 2D vector outline of an enclosure was designed and built with three layers of laser cut 3mm black Perspex. The top layer of material was a frame where the clear Perspex display could be placed. Seven RGB LEDs were chained together and interlinked within seven slots of the enclosure. Each LED was positioned within the frame to illuminate one designated segment (see Figure 4a). In order to isolate light emitted from an LED to a single designated segment, black inserts were designed and placed into the display. The width of cuts was increased to 1mm width and black material (3mm depth) was cut corresponding to cavities in the transparent display. The black material inserts (1mm width) isolated each of the seven sections of the SSD and occluded light rays reaching inactive segments. Several refinements were made to the position and design of the black inserts until a proficient implementation was found. As seen in Figure 4a-b, black inserts enable each segment to be illuminated individually without light effective adjacent segments. These black

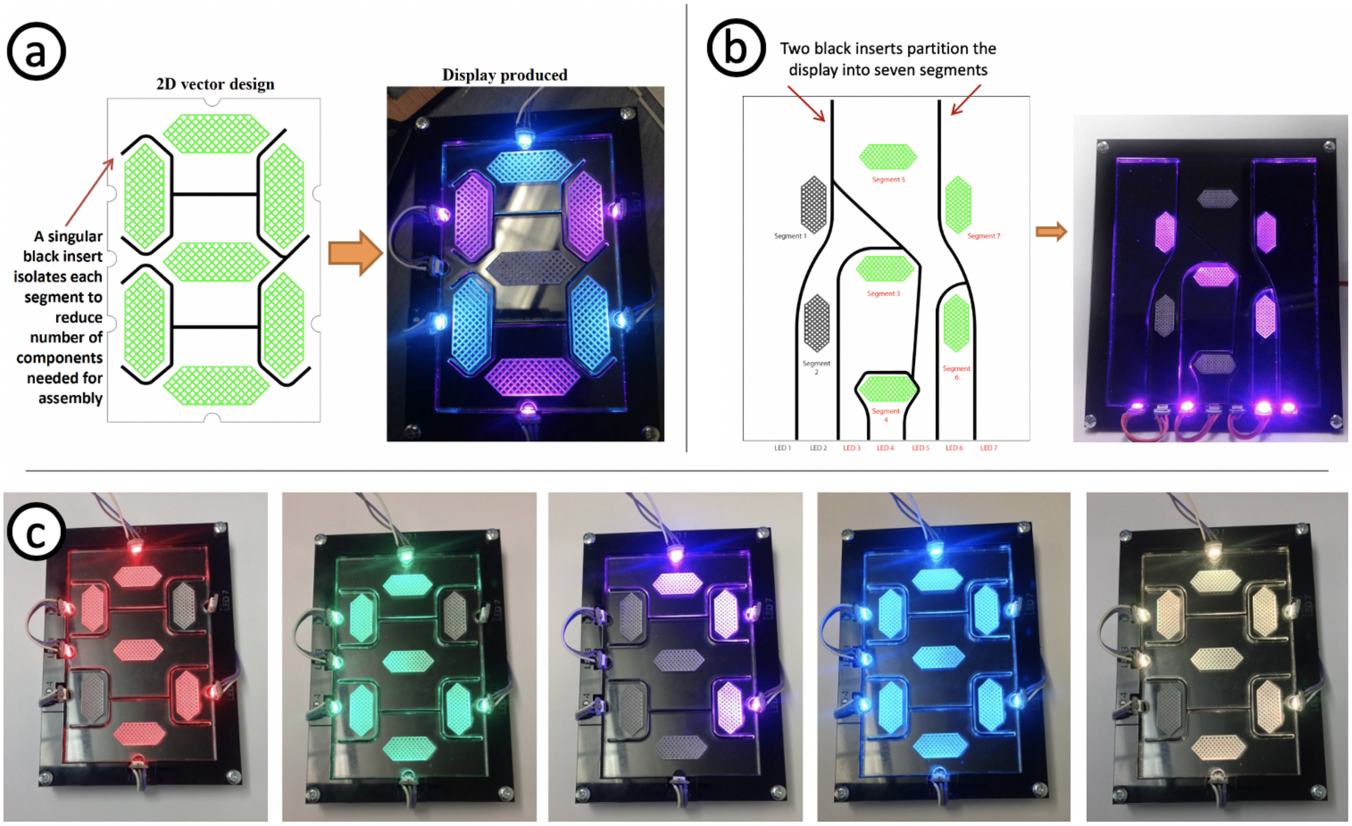

Figure 4: Our SSD design with black material inserts that isolates each segment of the display (a) and a second SSD displaying the number "4" were LEDs are only on the bottom of the display (b). A range of values displayed in a range of colours (c).

laser cut Perspex inserts occlude and stop light rays from reaching inactive segments.

The display is able to visualise each of the 128 states of an SSD with LEDs situated around all four sides of the enclosure. We shows examples of five states "5-9" in Figure 4c. To refine the design further, LEDs where positioned only at the bottom of the display. The second SSD prototype was fabricated using the same design approach, though the seven LEDs were situated only on the bottom of the frame (Figure 4b). Each etched segment had to be reduced in size and moved further away from the other to support the new black inserts design.

4 WATCH PROTOTYPE

Our demo prototype integrates the interface elements we describe earlier and applies them to a smaller scale wearable device. This final prototype incorporates the interactive FTIR properties of clear Perspex material to create a button light switch. The interface was conceptualised and developed based on the design and fabrication process used to create the original SSD interface. The watch is designed for small scale and displays current time using individual numeric figures sequentially on a single sheet of optically clear material (Figure 5a) that is situated within an enclosure that houses seven RGB LEDs (Figure 5b). An interactive button is used to activate the display (Figure 5c). When a user applies a sufficient level of force to the surface of the material, a change in light intensity measured by an LDR will occur. This is used as an activation command to display current time on the display.

4.1 LED Enclosure

First, a chain of seven RGB LEDs was soldered together. Each LED was designated to illuminating one segment of the SSD. A rectangular enclosure, consisting of six sides with finger edge joints was designed with seven cavities to house each of the LEDs. The LED chain was manually inserted into the enclosure (Figure 5a).

4.2 Display Design

We then developed a SSD interface design at a smaller scale for a watch display (Figure 5b). Although the enclosure for the LED chain is 90mm in length, the interface is much smaller to ensure discreteness as a ubiquitous device. The display integrates a generic SSD interface (40x40mm) with a rectangular extension that increases the length of the entire display by 10mm. By extending the width of the display we can accommodate the larger enclosure situating the chain of seven LEDs. See Figure 5b for final prototype. Initially black cuts were simply extended to the bottom of the display to isolate each of the individual LEDs. The width of cut was also decreased to 0.5mm in order to reduce the presence of black material

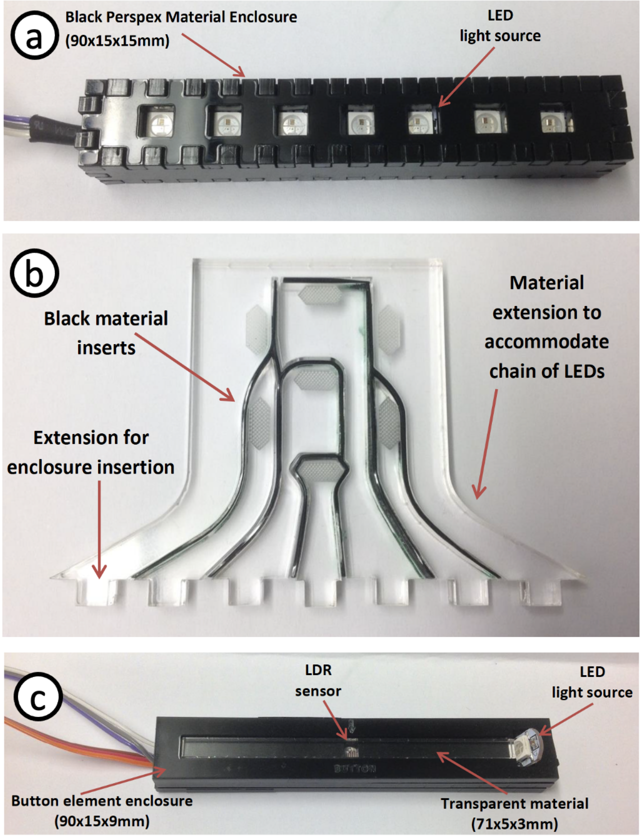

Figure 5: Our three main prototype elements used include a smaller LED enclosure (a), a smaller SSD display design (b), and an interactive button component (c).

in the interface. The initial display was cut from 5mm clear material with corresponding black material inserts. The whole interface consisted of five separate segments, two black inserts, and secured with acrylic adhesive.

4.3 Interactive Button

A separate enclosure was designed for the interactive button element (90x15x9mm). This was a scaled down version of the original design based on the initial button light switch. The button enclosure consists of three layers of black material with cavities for an LDR light sensor to be situated in the middle layer and another cavity for an LED in the top layer. See Figure 5c for final prototype. User input must be configured with consideration of ambient light. First, light intensity average is calculated when no pressure is applied to the surface, this is used as an actuation threshold for the watch. Secondly, light intensity average is calculated when no pressure applied to the surface. This is used as a threshold to deactivate visualisation if unintentional interaction occurs. Ambient light in the environment must also be taken into consideration as this disrupts readings from an LDR which is very sensitive. Including a capacitor to the circuit in further work can help eliminate ambient light noise from the LDR reading.

4.4 Prototype Integration

Once the final interface was assembled a watch strap was designed to hold the watch on a human wrist (Figure 6). Hinges secured with adhesive enabled the user to adjust the tightness of the strap. The combined light enclosure, interface, and button produced a wearable watch with interactive capabilities. The interface visualises each digit of time in sequential order once enough finger pressure is applied to the button. Performance was tested in ambient light for quality in visualisation and interaction. Interactivity of the button was efficient with and without ambient light present. The combination of the LED enclosure, display, and button enabled fabrication of a purposeful interactive device that can be used in both darkness and daylight as seen in Figure 6. By applying our fabrication approach for wearable technology we demonstrated that interface scale should not be an issue in the design space. However the large size of LEDs used meant that the light enclosure could not be smaller. In terms of visualisation, the luminosity of figures could be enhanced by limiting the space between the LEDs. With further refinements to the discreteness of electric components (e.g., by using smaller LEDs), the device could be scaled down much more. Nevertheless, visualisation of meaningful information on transparent surfaces does enable further exploration of the design space for novel interfaces.

In terms of interactivity, the button element was able to activate the display when ambient light levels within the test environment stayed constant. If levels of ambient light increased, a new threshold level had to be set to accommodate the change, otherwise, the button would activate in ambient light. The watch device is easy to customise by simply replacing detachable sections with alternative components. The transparent display is detachable from the main enclosure. This allows users create new interface elements and replace them easily without the need to fabricate a whole new device. Cost of material and lead time as a result is greatly reduced compared to 3D printing a device as a whole. This brings new opportunities for rapid prototyping without the need to wait for creating a whole new object.

5 DISCUSSION

In this work we aimed to explore how we could embed interactivity and visualisation capabilities into laser-cut substrates for rapid prototyping interfaces.By utilising light properties of clear Perspex through laser cutting, we devised a simplistic method of designing and producing interactive elements and visual displays for novel interfaces. We then integrated these active elements to create a fully functioning watch prototype. The process described in our work outlines fundamental techniques for designing and developing similar active components that can be customised and altered to an individual's needs and specifications. Laser cutting enables an accessible method of fabricating rapid prototypes, and as a result – a rapid process of exploring and designing without the need to create a whole new object has emerged. The electronic components and material used throughout this project are low cost and easily implemented without need for advanced technical skills. The design space demonstrated within this work can also be expanded further by exploring more complex tangible interface designs with arbitrary shapes in future work. Practically, with specific applications in mind

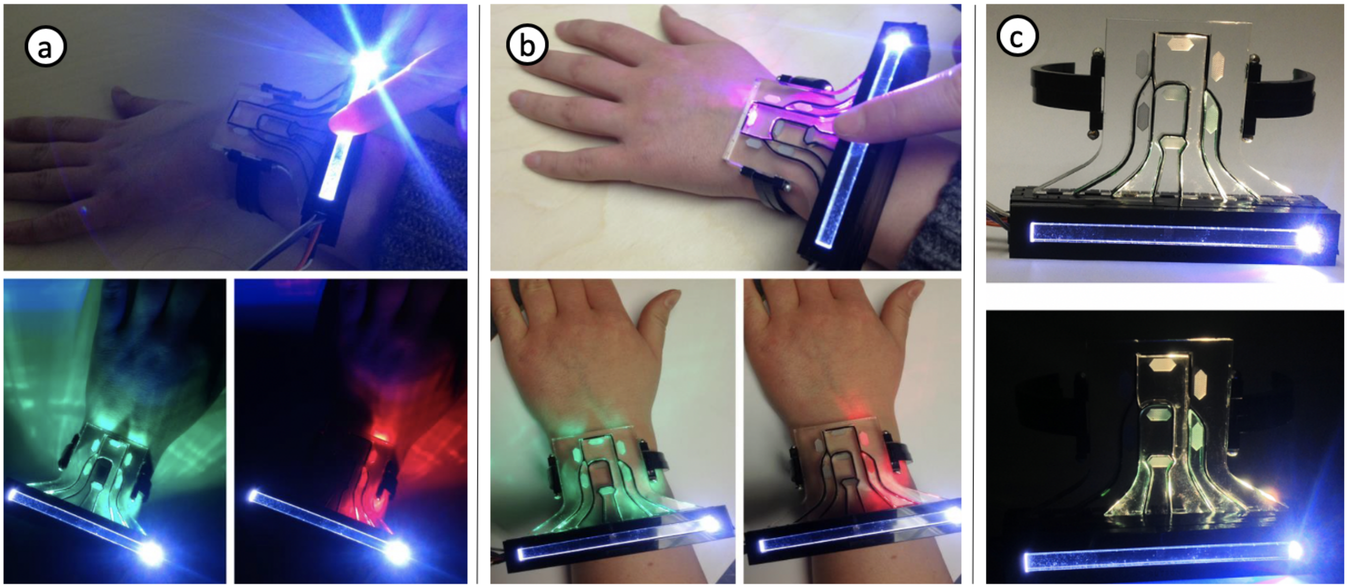

Figure 6: Design and applied SSD with black material insert that isolates each segment of the display (a). Single layer SSD design with black inserts and final implementation of an SSD displaying the number "4" (b).

such as health care and flexible displays. Our method is a simple yet creative approach to design and fabricate novel interfaces to be utilised by a large range of users who do not have access to optical resin 3D printers or possess 3D modelling skills.

In summary, fabricating interfaces from a single clear sheet of material can enable new kinds of novel devices such as wearables. Using the example of a smart watch ensures the SSD design can be used effectively to display meaningful information in multiple colours on a transparent interface at a small scale in a novel way. We want to broaden the availability of fabrication methods to enable accessible, sustainable and affordable prototyping.

5.1 Limitations

In terms of interaction capabilities, the main limitation of the current method is that user input threshold light intensity must be calibrated manually when ambient light intensity within the environment changes. As such, the stability of interactive devices fabricated using the process is limited if constant resets are needed to calculate the user input threshold. To combat this, an algorithm could be implemented to eliminate ambient light data from LDR readings, or a capacitor could be added to the LDR circuit which would also reduce discrepancies in ambient light readings, although an extra electronic component would be needed for fabrication.

We also discovered that when ambient light is present some segments are occluded by others and are not as prominent, further testing to eliminate this is required. Additionally, only finger based interaction was explored, and there are alternative input possibilities (e.g., stylus), but given the prevalence of touch based interaction we believe our methodological focus is justified. Finally, we could not have predicted that the laser cutter used throughout the project varied in quality and precision due to maintenance issues, and resulting laser damage to the material decreased the optical illumination quality.

5.2 Future Work

This work has the scope to be extended in several ways. For example, exploring effects of light intensity in a range of material lengths and widths to further investigate impact on larger scale implementations and particularly by ascertaining the optical properties of materials other than Perspex. Further scaling down the prototypes may also be possible if we use smaller surface-mount LEDs for the visual display. We could also refine the etching style to display more detailed information.

In terms of prototyping, we could also explore a range of applications other than our wearable watch prototype such as other 2D planar and non-planar displays, such as implementing curved 3D surface displays or displays with extrusions and arbitrary shapes. To support this, we can use an WYSIWYG approach where a user would see a simulation beforehand of what the visual display of their design before it is laser cut. Additionally, our fabrication approach could be further extended by adding algorithmic generation of interface designs. A 2D vector design system could be developed where users draw their interface segments, and black insert cuts can be algorithmically generated. Using computational geometry algorithms, such as Voronoi diagrams or Delaunay triangulation, geometric paths could be computed in order to isolate each segment based on the nearest neighbour concept. This would reduce the need for a user to manually design black insert cuts for an interface, and enable faster, smoother prototyping. Black inserts can also be redesigned with sharper angles to accommodate light sources further away from the etched display, such interfaces can be highly robust and even submerged in water.

6 CONCLUSION

In this paper we have demonstrated a simple, accessible, and affordable alternative approach for rapid prototyping of novel interactive interfaces. Specifically, by using low-cost widely available optically clear Perspex and adding interactivity with basic LDR light sensors and LEDs. Our outline description of the process should enable replication of similar devices by researchers and makers. The use of a laser cutter enables rapid fabrication of prototypes without the need for extensive knowledge of 3D modelling. The acrylic material we used, specifically Perspex, can be easily obtained at low cost and offers higher quality finish compared to resin, Acrylonitrile Butadiene Styrene, or Polylactic Acid used for 3D printing. By embedding interactivity and visualisation capabilities into laser-cut substrates using simple cutting and etching techniques, together with low-cost interaction principles such as FTIR [9], we are able to rapidly fabricate novel transparent interfaces with just three active components. To conclude, this work aims to leverage low-tech solutions to build high-tech advances for the development of novel tangible interfaces.

ACKNOWLEDGMENTS

This research was supported by Amazon Web Services in the Oxford-Singapore Human-Machine Collaboration Programme.

REFERENCES

- [1] Jason Alexander, Anne Roudaut, Jürgen Steimle, Kasper Hornbæk, Miguel Bruns Alonso, Sean Follmer, and Timothy Merritt. 2018. Grand challenges in shape-changing interface research. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–14.
- [2] Patrick Baudisch, Stefanie Mueller, et al. 2017. Personal fabrication. *Foundations and Trends® in Human–Computer Interaction* 10, 3–4 (2017), 165–293.
- [3] Eric Brockmeyer, Ivan Poupyrev, and Scott Hudson. 2013. PAPILLON: designing curved display surfaces with printed optics. In *Proceedings of the 26th annual ACM symposium on User interface software and technology*. 457–462.
- [4] Tom Carter, Sue Ann Seah, Benjamin Long, Bruce Drinkwater, and Sriram Subramanian. 2013. UltraHaptics: multi-point mid-air haptic feedback for touch surfaces. In *Proceedings of the 26th annual ACM symposium on User interface software and technology*. 505–514.
- [5] Aluna Everitt and Jason Alexander. 2017. PolySurface: a design approach for rapid prototyping of shape-changing displays using semi-solid surfaces. In *Proceedings of the 2017 Conference on Designing Interactive Systems*. 1283–1294.
- [6] Aluna Everitt and Jason Alexander. 2019. 3D Printed Deformable Surfaces for Shape-Changing Displays. *Frontiers in Robotics and AI* 6 (2019), 80.
- [7] Mike Fraser, Jingqi Liu, Jenna Shapiro, Joshua Taylor, and Aluna Everitt. 2019. Digital-is-Physical: How Functional Fabrication Disrupts Ubicomp Design Principles. In *Proceedings of the Halfway to the Future Symposium 2019*. 1–5.
- [8] Daniel Groeger and Jürgen Steimle. 2019. LASEC: Instant Fabrication of Stretchable Circuits Using a Laser Cutter. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–14.
- [9] Jefferson Y Han. 2005. Low-cost multi-touch sensing through frustrated total internal reflection. In *Proceedings of the 18th annual ACM symposium on User interface software and technology*. 115–118.
- [10] Trevor Hogan, Eva Hornecker, Simon Stusak, Yvonne Jansen, Jason Alexander, Andrew Vande Moere, Uta Hinrichs, and Kieran Nolan. 2016. Tangible Data, explorations in data physicalization. In *Proceedings of the TEI'16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction*. 753–756.
- [11] Yvonne Jansen, Pierre Dragicevic, Petra Isenberg, Jason Alexander, Abhijit Karnik, Johan Kildal, Sriram Subramanian, and Kasper Hornbæk. 2015. Opportunities and challenges for data physicalization. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. 3227–3236.
- [12] Eric Markvicka, Guanyun Wang, Yi-Chin Lee, Gierad Laput, Carmel Majidi, and Lining Yao. 2019. ElectroDermis: Fully Untethered, Stretchable, and Highly-Customizable Electronic Bandages. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–10.
- [13] Catarina Mota. 2011. The rise of personal fabrication. In *Proceedings of the 8th ACM conference on Creativity and cognition*. 279–288.
- [14] Stefanie Mueller, Bastian Kruck, and Patrick Baudisch. 2013. LaserOrigami: laser-cutting 3D objects. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 2585–2592.
- [15] Stefanie Mueller, Pedro Lopes, and Patrick Baudisch. 2012. Interactive construction: interactive fabrication of functional mechanical devices. In *Proceedings of the 25th annual ACM symposium on User interface software and technology*. 599–606.
- [16] Martin Nisser, Christina Chen Liao, Yuchen Chai, Aradhana Adhikari, Steve Hodges, and Stefanie Mueller. 2021. LaserFactory: A Laser Cutter-based Electromechanical Assembly and Fabrication Platform to Make Functional Devices & Robots. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. 1–15.
- [17] Valkyrie Savage, Ryan Schmidt, Tovi Grossman, George Fitzmaurice, and Björn Hartmann. 2014. A series of tubes: adding interactivity to 3D prints using internal pipes. In *Proceedings of the 27th annual ACM symposium on User interface software and technology*. 3–12.
- [18] Karl Willis, Eric Brockmeyer, Scott Hudson, and Ivan Poupyrev. 2012. Printed optics: 3D printing of embedded optical elements for interactive devices. In *Proceedings of the 25th annual ACM symposium on User interface software and technology*. 589–598.
- [19] Junichi Yamaoka, Mustafa Doga Dogan, Katarina Bulovic, Kazuya Saito, Yoshihiro Kawahara, Yasuaki Kakehi, and Stefanie Mueller. 2019. FoldTronics: Creating 3D Objects with Integrated Electronics Using Foldable Honeycomb Structures. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–14.
- [20] Junyi Zhu, Lotta-Gili Blumberg, Yunyi Zhu, Martin Nisser, Ethan Levi Carlson, Xin Wen, Kevin Shum, Jessica Ayeley Quaye, and Stefanie Mueller. 2020. CurveBoards: Integrating Breadboards into Physical Objects to Prototype Function in the Context of Form. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–13.