ECPlotter: A Toolkit for Rapid Prototyping of Electrochromic Displays

Jensen, Walther; Löchtefeld, Markus

Published in:
Proceedings of the 21st International Conference on Mobile and Ubiquitous Multimedia

DOI (link to publication from Publisher):
10.1145/3568444.3568466

Publication date:
2022

Document Version
Accepted author manuscript, peer reviewed version

ECPlotter: A Toolkit for Rapid Prototyping of Electrochromic Displays

WALTHER JENSEN, Aalborg University, Denmark

MARKUS LÖCHTEFELD, Aalborg University, Denmark

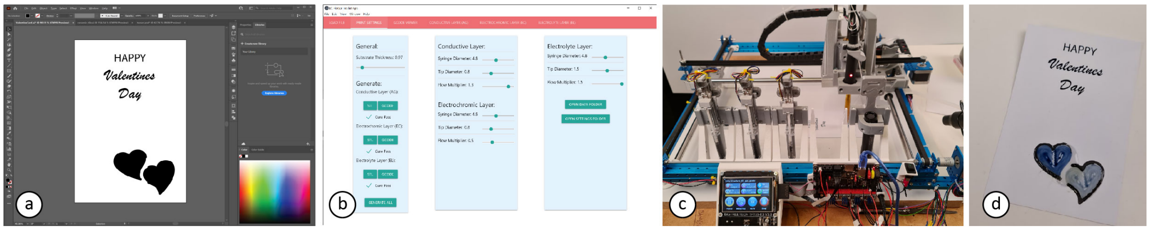

Fig. 1. ECPlotter enables designers to rapidly prototype electrochromic displays in a two-step fabrication process. After designing the display (a), our toolkit generates printer instructions (b), and then automatically prints and cures all the layers (c) allowing displays to be printed on a variety of substrates (d).

ECPlotter is a prototyping toolkit for the fabrication of electrochromic displays. By syringe depositing conductive, electrochromic and electrolyte inks, and curing the inks in one step, we can rapidly create displays in a single integrated process. In contrast to existing methods, such as screen-printing, ECPlotter allows for quick early prototyping with minimal human intervention and makes the process more accessible since the fabrication is automated. Our software pipeline enables designers to convert graphics directly into an instruction set that can be interpreted by the printer which includes automatic heat and UV curing passes after ink depositing. Finally, we demonstrate its capabilities by printing on a variety of substrates.

CCS Concepts: • **Human-centered computing → Interface design prototyping**; *Displays and imagers*; User interface design.

Additional Key Words and Phrases: Electrochromic Displays, Fabrication, Rapid Prototyping, Transparent and Flexible Displays

ACM Reference Format:

Walther Jensen and Markus Löchtefeld. 2022. ECPlotter: A Toolkit for Rapid Prototyping of Electrochromic Displays. In *21th International Conference on Mobile and Ubiquitous Multimedia (MUM 2022), November 27–30, 2022, Lisbon, Portugal.* ACM, New York, NY, USA, 19 pages. https://doi.org/10.1145/3568444.3568466

1 INTRODUCTION

One of the long-term visions in Human-Computer Interaction is a world in which digital user interfaces are seamlessly integrated with the physical environment until the two are indistinguishable from one another [52]. In such a future, every surface will become interactive. Besides integrated sensing possibilities (e.g., [55] and [2]), we will also see pervasive display surfaces where graphics that in today's world are mostly static will become interactive and context aware [47].

One promising technology to accomplish such seamless integration are electrochromic displays. In contrast to other technologies, such as electroluminescent or fluorescent displays that emit light and thus standout from non-digital media, electrochromic materials are non-light emitting. This allows them to seamlessly blend with non-digital objects and printed graphics that surround them. However, so far, prototyping and fabricating electrochromic displays requires manually screen printing the multi-layer display stack [16].

To prepare the screens for screen-printing, designers have to follow a process of manually coating the screen mesh with emulsion, waiting for it to dry, exposing it to light, rinsing uncured emulsion, and drying again before being able to use it for printing. For each layer in the electrochromic display stack (conductive and electrochromic or more) a new screen needs to be prepared and thus the preparation process must be repeated multiple times. This comes with several drawbacks: First, it is very time-consuming and labor-intensive since the preparation process of one screen can take between six to ten hours [16], thereby inhibiting rapid prototyping and design iterations. Second, the process of aligning multiple layers on top of each other can be imprecise and thus the overall display resolution is limited by the manual capabilities of the user. In addition, the thickness of each layer impacts display properties, such as the saturation and switching speed, and is difficult to control in a screen-printing process. Finally, if layers are applied unevenly, the display may have visual defects, such as areas with varying saturation across the display area.

In this paper, we present a new fabrication hardware (ECPlotter) for prototyping electrochromic displays based on syringe depositing using a customized 2D plotter. Syringe depositing has recently seen a rise as an emergent technology for bio-printing and has been used to print bacteria, gels and liquids [6, 11, 28, 29, 33, 50]. However, to our knowledge this is the first time a syringe printing system has been created for printing electrochromic displays and thereby not only extending the prototyping options for electrochromic displays but also demonstrating further the possibilities of syringe printing. ECPlotter contains specific tools for each layer (conductive, electrochromic, electrolyte, heat curing and UV curing) in the printing process of an electrochromic display. This reduces the imprecision of the screen-printing process presented in [16], reduces the time from design to finished prototype and the syringe depositing enables precise control of deposited ink. Furthermore, if researchers, creatives or those interested in prototyping electrochromic displays they only need a small table area for the printer as opposed to what is required for screen-printing. Thus, by using ECPlotter, we can rapidly prototype and iterate on the design of electrochromic displays as well as print on various substrates giving more freedom in prototyping.

In summary, we contribute:

- an end-to-end pipeline for rapidly fabricating electrochromic displays using a customized CNC syringe depositing system;
- a software toolkit that supports designers in creating electrochromic displays and automatically exports the instructions for the *ECPlotter* printer
- a set of application examples demonstrating electrochromic displays for wearables, flexible paper interfaces, and rigid ceramic tiles;

In the remainder of the paper, we will first review the related work and then discuss each of the contributions listed above in order.

2 RELATED WORK

2.1 Display Technologies for HCI Research

A range of display technologies use either heat (thermochromic), light (photochromic), or magnetic (magnetophoretic) stimuli to update the displayed content. For instance, ShaderPrinter [46] uses the heat generated from a laser to switch thermochromic materials from transparent to colored. PhotoChromeleon [22] uses light of various wavelengths from an office projector to switch a mix of photochromic dyes from transparent into a range of different colors. Finally, Sweepscreen [35] can switch its display color depending on the polarity of the magnetic field.

Most research, however, has focused on electrically-driven displays since they allow for faster switching speeds. One such technology that has been widely explored in HCI are electroluminescent displays, which emit light when a voltage is applied. HCI researchers have explored how to fabricate electroluminescent displays for a wide range of use cases, such as making them stretchable (Stretchis [54], SiliconeDevices [39]), applicable to large surfaces (Sprayable User Interfaces [53]) as well as curved object geometries (ProtoSpray [10], ObjectSkin [9]). In addition, researchers demonstrated how to fabricate displays of different visual complexity, ranging from simple shape, to segment, and matrix displays (PrintScreen [44], Amiraslanov et al. [3], Ivanov et al. [14]). While there is a large body of knowledge on how to fabricate electrolumiscent displays using screen-printing or inkjet printing (PrintScreen [44]) as well as spraying (Sprayable User Interfaces [53]), researchers have only recently started to investigate how to develop such techniques for the fabrication of non-light emitting displays, which better integrate with the environment. Two technologies in this space are electrophoretic display (‘e-ink’, see Sweeney et al. [47]) and electrochromic displays. While electrophoretic displays require advanced manufacturing techniques for the microcapsules, electrochromic displays use materials that allow for easier experimentation.

2.2 Electrochromic Displays

In addition to being non-light emitting, electrochromic displays hold their display content even when removed from an energy source, resulting in a low power consumption [4]. While the first electrochromic displays were limited to a single-color only, recently researchers have also shown how to fabricate multilayered color displays (Naijoh et al. [40]). Electrochromic displays have seen a wide variety of different applications, from window panels that darken to prevent sunlight from entering the building (Granqvist et al. [8], Iuliano et al. [13]), to ambient information and notifications (Müller et al. [37], Vyas et al. [49]), and privacy screens applied to transparent office walls (Telhan et al. [48]). So far, electrochromic displays have mainly been fabricated in a mass-manufacturing setting (Coleman et al. [3]). More recently, researchers also investigated how to create electrochromic displays in smaller volumes using a semi manual manufacturing process that uses an industrial screen-printing press to apply each layer of the display stack one after another (Andersson et al. [1]). TransPrint [16, 31, 32] extends this line of work by presenting a fabrication process for screen-printing electrochromic displays, which uses an off-the-shelf hardware setup that can be used in makerspace activities [18] by non-experts to produce their own display designs. Based on this technique also a variety of prototypical applications have been developed in the past, ranging from simple user interfaces [4], notifications [36], hybrid board games [21], over ambient lighting [19, 20], wearables [5, 15, 17], as part of a learning activity [30] or in a soft robot [34]. For our research, we built onto this work and will try to automate the fabrication process of electrochromic displays using printed electronics.

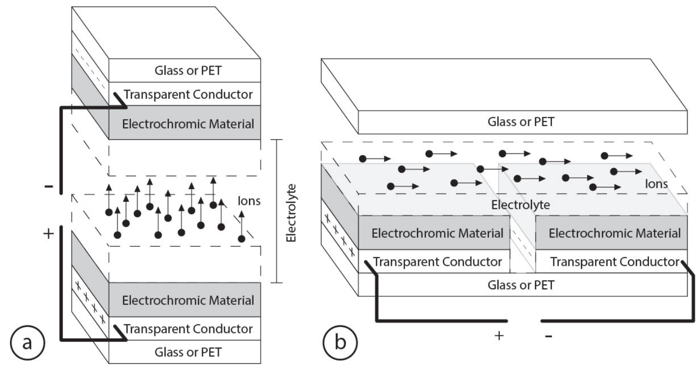

Fig. 2. General representation of electrochromic displays. (a) Vertical stack: Ions move from the bottom to the top and vice versa through the electrolyte, (b) Co-planar stack: ions move from left to right and vice versa through the electrolyte.

2.3 Printed Electronics

Printed electronics remove manual labor from the fabrication process by creating the circuitry using automated inkjet printing of conductive and other functional inks (Instant Inkjet Circuits [25]). Over the last years, inkjet printing of functional inks has seen many applications, from printing different types of user input elements (Cuttable Multitouch Sensor [42], Multi-Key Touch Input [23], Gong et al. [7], FoldIO [43]) to various output capabilities (Printed Tactile Display [24]). By using transfer paper as the substrate, inkjet printing can also be used to create displays on curved surfaces (SkinMarks [51]) and to create transfer layers for more complex fabrication processes, such as those based on hydrographics (ObjectSkin [9]). Recently, researchers also started to investigate how to inkjet print display elements. FunCushion [12] uses transparent fluorescent ink to print display patterns onto cloths; the patterns can be made to glow with an ultraviolet light source manually embedded inside the cloths. In PrintScreen [44], the authors used an inkjet printer to print the conductive traces for the display stack of electroluminescent displays similar to [25]. Building on this Khan et al. [26] presented a method that allows for multi-ink functional printing on commodity printers for realizing multi-material functional devices. While using commercial ink-jet printers would democratize the prototyping of displays to a very high degree, our early experimentation lead to several problems of inks drying out quickly and rendering the printer useless. Furthermore, commercial ink-jet printers would also require multiple printing paths for drying (or UV curing) the inks as well as limit the potential substrates the displays can be printed on. Therefore, we decided for ECPlotter to develop a custom hardware platform, that simplifies the process to a single-step print and allows to print on a variety of different substrates (e.g., ceramic tiles that can not be used with a normal printer).

3 CHALLENGES

Being able to rapidly prototype electrochromic displays requires solving several challenges related to the display materials and the particular characteristics of the printing process. To provide background information on why these challenges exist, we briefly review the basic working principle of electrochromic displays which consist of four different materials:

Electrochromic: Electrochromic materials can persistently and usually reversibly change their optical properties, i.e., transition from transparent to colored and vice versa. The change in color occurs when ions move from one electrochromic area to another electrochromic area (Fig. 2). Thus, stable electrochromic displays always need at

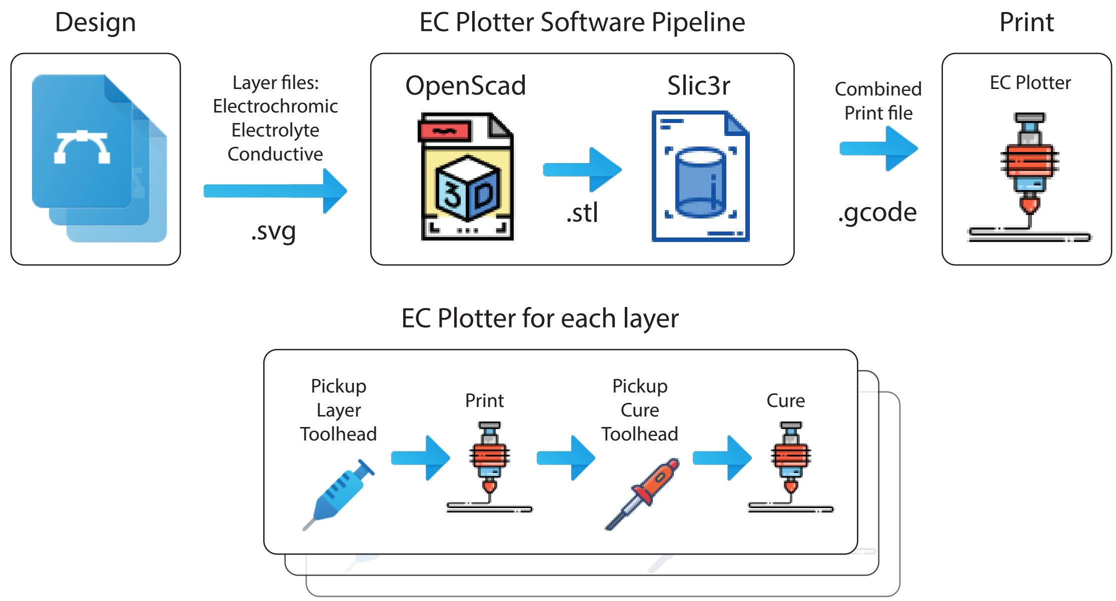

Fig. 3. ECPlotter Toolkit Overview: The user creates a design and exports the required layers as svg files. The ECPlotter toolkit converts the files to a combined print file the ECPlotter can interpret. When printing, the ECPlotter selects the toolhead for the layer to be printed, prints, picks up the cure toolhead and cures the layer. This is repeated for each layer without user intervention.

minimum two electrochromic areas between which ions are exchanged to cause a change in saturation, with one area becoming more saturated and the other becoming less saturated as a result. The challenge with electrochromic inks are printing the correct amount i.e. thickness to ensure the highest possible transparency while at the same time also ensuring the highest possible color contrast when visible. Too much ink and there will be nearly no visible change in transparency and too little and the color will not be properly saturated.

Electrolyte: To enable the movement of ions between the two electrochromic areas, an ion conductor that connects them both is necessary. The ion conductor is a material called electrolyte which for electrochromic displays is typically in a UV curable gel form. This gel form has a high viscosity which makes it unsuitable e.g., for commercial ink-jet printers. Therefore, in the current production of electrochromic displays the electrolyte is applied manually resulting in uneven distribution as well as a labor intensive work-step. The challenge of applying electrolyte is ensuring an even distribution that has enough thickness to allow ion conduction at every part of the display.

Conductor: To move ions from one electrochromic area to another, a small electrical charge (<10mA, 1.4 - 3V) is required. This means that a conductive lead needs to be added for each electrochromic field. For example in [16] the authors chose to use indium tin oxide (ITO) (a transparent metal) as the conductor for their screen-printed displays. However, ITO is a toxic material that can only be applied in highly controlled laboratory settings. One way of minimizing this overhead, is using an electrochromic material that is conductive itself, such as PEDOT:PSS, as it then only requires a direct conductive lead to the ink field resulting in an extra layer. For screen printing however this would mean that a separate screen needs to be prepared which is again labour intensive. The challenge here is finding a conductive ink for the leads that can be cured at low temperatures.

Substrate Layer: Finally, the substrate layer is used to enclose the display, i.e. to prevent dust and dirt from affecting the display quality, to encapsulate the electrolyte and to provide overall stability. This is typically either glass or thin sheets of polyethylene terephthalate (PET). This limits the potential use cases and don't reflect the whole capabilities of electrochromic displays. Electrochromic displays exist in both the vertical stack design and the co-planar stack design as shown in Fig. 2, with ions either moving from the bottom to the top or from left to right and vice versa through the electrolyte. While the vertical stack allows for interesting overlays of two ink-fields, these can also lead to visual artefacts and it also means that the display usually is thicker. Therefore, for ECPlotter we decided in the first iteration to only focus on the co-planar stack. This also removes the need for a secondary substrate. However, the challenge is finding substrates that allow for printing without impairing the visual quality of the displays.

Summary: In the following list are the challenges in a short form for later reference.

(1) Deposit correct amount of electrochromic ink.
(2) Even distribution of electrolyte.
(3) Find or develop low temperature curable conductive ink.
(4) Find substrate(s) with minimal impairment of visual quality.

4 ECPLOTTER

With the ECPlotter prototype we present a novel tool for early rapid prototyping of electrochromic displays that allows printing an entire display in a single step and on a range of different substrates (e.g., glass, paper, photo paper and fabric). By utilizing an automatic tool changing system we can print all required inks (conductive, electrochromic and electrolyte) in one process including the needed heat and UV curing steps that are required for each step (Fig. 3). This eliminates the need to move the substrate for curing in between each layer which were necessary in previous fabrication methods [16]. Having all the steps performed in one process allows for more intricate and precise prints as the typical registration errors in between layers no longer pose a problem; and precision of prints is now restricted by hardware limitations rather than human errors.

4.1 Hardware Implementation

The ECPlotter is built on the frame of a Makeblock XY-Plotter Robot Kit with several custom designed parts. As the original kit was designed to carry minimal weight (pens) in its XY gantry it was not strong enough to carry a tool changing gantry with a stepper motor for height control. Several parts were upgraded to support the extra weight, reduce unsteadiness and vibrations and enable support for printing on substrates with differing thicknesses. First, all the rods were changed from the original 8mm to 12mm h6 smooth rods (Fig. 4,a) to add more stability and the ability to support more weight. Second, the main gantry (Fig. 4,b) was redesigned from the ground up to support height control and tool changing. Third, five tool holders (Fig. 4,d) were added to the frame to support the required tools. Finally, for the control board (Fig. 4,e) we chose a more powerful and computational capable board (BigTreeTech SKR Turbo 1.4) with improved stepper drivers (Trinamic TMC2209) and an attached touch display. The upgraded drivers enable software current control and improves stability for each of the steppers and the upgraded mainboard enabled us to create a custom Z height endstop which we use to home the needle tip position on the Z axis. A 310mm by 310mm by 3mm borosilicate glass functions as the substrate bed. The Z homing is calibrated to ensure a height of 0 on the Z axis has the needle tip slightly resting on the glass bed. Finally, the display provides live feedback and enables on the fly control for potential changes during printing (e.g., baby stepping of the Z height to adapt to the substrate). Furthermore,

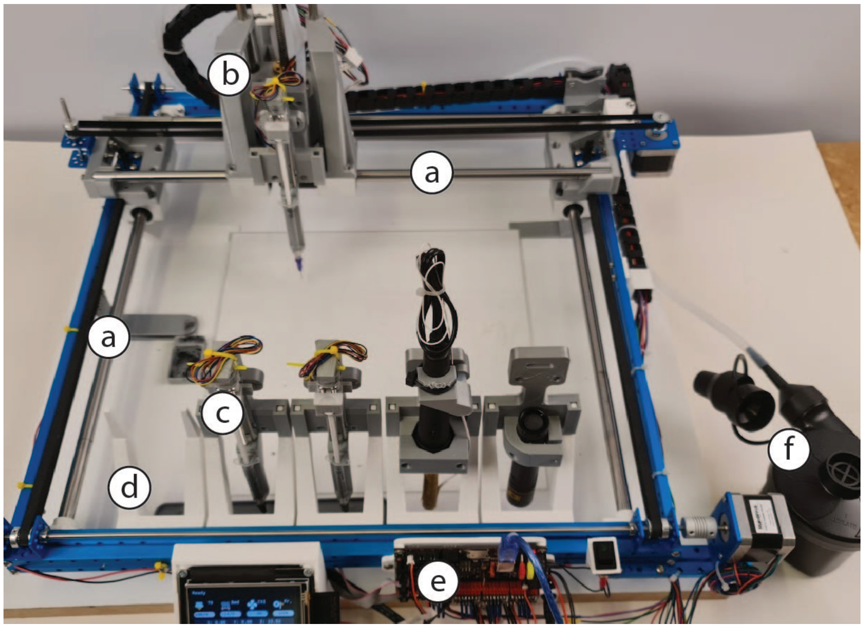

Fig. 4. The ECPlotter hardware: (a) resized 12mm rods, (b) gantry with height control and tool changing capabilities, (c) syringe depositing tool, (d) tool holder, (e) new control board with display and (f) air pump.

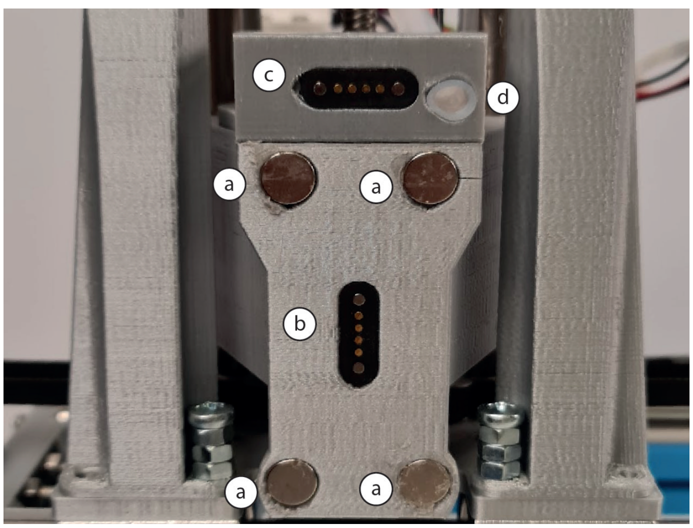

Fig. 5. The printers gantry with (a) Neodymium magnets for connecting to the tools, (b and c) magnetic pogo connector for controlling tool stepper motors and powering the heat gun tool, (d) air hose for blowing air through heat gun tool.

the upgraded mainboard can be controlled by the open-source 3D printer firmware Marlin which is using the same GCode used in a large range of CNC machines and 3D printers.

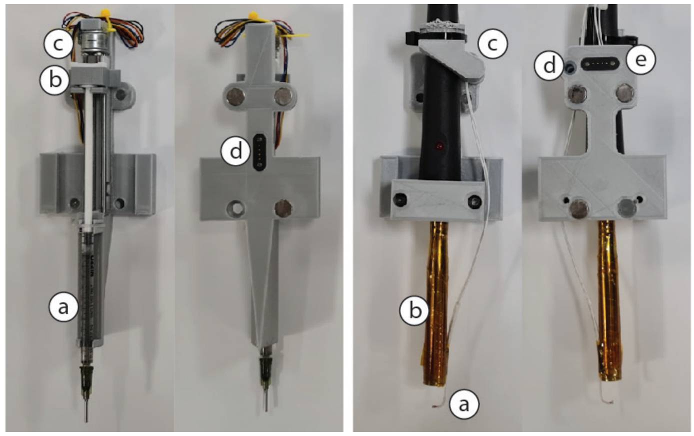

Fig. 6. Two of our tools integral to the printing process. *Left:* The syringe depositor tool consisting of a syringe with an attached tip (a), a coupler connecting the stepper motor with the syringe (b) a small linear stepper motor (c) and a magnetic four pin pogo connector (d). *Right:* The heat gun used for curing conductive and electrochromic inks consisting of a thermistor (a), a 12v soldering iron (b), an air connector (c and d), and a magnetic four pin connector (e).

Tool changing: To enable attaching and detaching tools, the gantry and each tool is provided with four round Neodymium magnets (10mm diameter, 2mm thick, approximately 2kg adhesive strength). The magnets (Fig. 5,a) provide easy snap-on and release of the tools using the built-in strength of the gantry's movement. To provide electrical current for the syringe depositor and heat gun tool the gantry has two four pin magnetic pogo connectors (comparable to Apple's MagSafe); one in the middle (Fig. 5,b) and one at the top (Fig. 5,c) of the front gantry surface. The middle connector provides connection to the stepper motor driving the depositing of ink and the top connector provides two connections to power the heat gun and two pins to measure the temperature of the air being blown out of the heat gun. When not in use, the tools are stored on a custom 3D printed holder that is attached to the front of the XY plotter where they can be picked up by the gantry (compare Fig. 4,c and d).

Syringe depositor tool: Depositing ink is achieved by a small linear stepper motor (Walfront, 12v rated, Fig. 6,left,c) actuating a 1ml syringe (Fig. 6,left,a) with a needle tip. The size of the needle can be changed depending on the ink being printed, we use a 21-gauge (0.8mm) needle for printing electrochromic ink, 19-gauge (1.0mm) or 18-gauge (1.2mm) for conductive ink and 14-gauge (2mm) for electrolyte. A 3D printed coupler (Fig. 6,left,b) is screwed onto the linear stepper nut and provides a fixing point for the syringe plunger. The frame of the tool is designed for easy changing and refilling of syringes.

Heat gun tool: Curing the conductive and electrochromic ink requires heating up the material to evaporate the water in the inks. Previous fabrication methods have used ovens or hand-held heat guns for this process. Using ovens requires moving the substrate from the print area to the oven introducing possible registration errors between print passes and with hand-held heat guns it can be difficult to control the temperature. Our heat gun tool consists of a standard hand-held soldering iron (12V rated, Fig. 6,right,b), a thermistor for measuring the temperature (Fig. 6,right,a), a custom designed air pump connector (Fig. 6,right,c and d) and a four pin magnetic connector (Fig. 6,right,e). By not attaching a soldering tip to the iron and drilling a hole in the handle air can be pushed through internally in the soldering iron creating a small heat gun. The thermistor is placed approximately 1cm from the mouth the iron and works in a closed loop with the mainboard to control the heat of the air coming out of the iron. Air is blown through a silicone tube

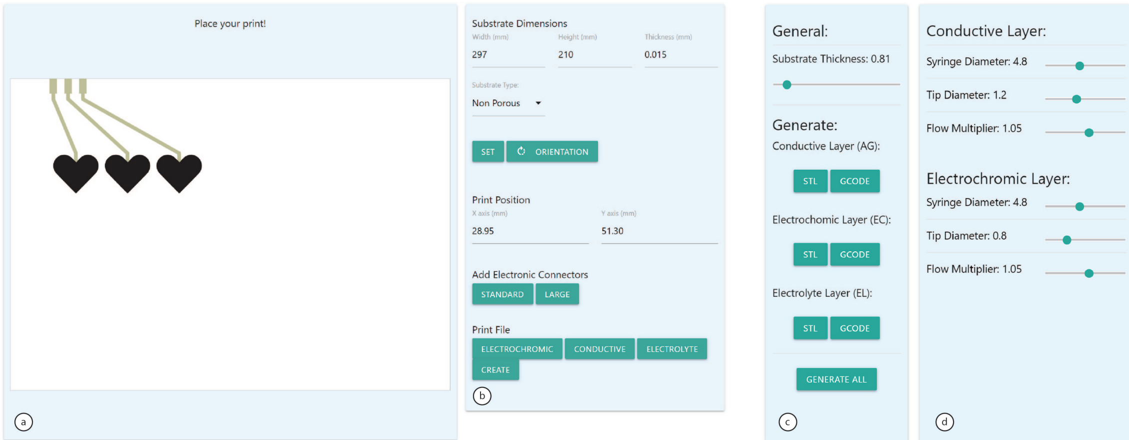

Fig. 7. The simple and advanced parts of the toolkit application. (a) The interface to set the position of a simple print and the electronic connectors on the substrate. (b) Lets the user enter the dimensions of the substrate and whether it is porous or not. Further more this interface allows the user to easily add electronic connectors to the electrochromic parts. (c) Advanced users can select which layer and type of file to generate or a full print file. (d) Furthermore, advanced users can adjust the syringe and tip diameter, and flow multiplier for each layer.

(6mm internal diameter, Fig. 5,d) from an air pump (Tenzo Electric, 280 L/min rated, Fig. 4,f) placed next to the printer. Through calibration of the temperature we found that running the air pump at 3v provides enough air pressure to sufficiently blow on the printed material while allowing the iron to heat the air. If more voltage is applied to the air pump we drastically increase the time it takes for the iron to heat the air to the required temperature of 90-110°C (this can be adapted to e.g., prevent any damage to the used substrate material that is printed on).

UV curing tool: The electrolyte cures when exposed to UV light and in order to provide this functionality the last tool holds a UV flash light (Alonefire, 10W, 3.7V, 365Nm). The tool itself is not connected to the mainboard and the flashlight is battery driven. We've chosen this option so that it would be possible to easily change to a flashlight that uses a different wavelength if needed. However, it means that the flashlight needs to be manually turned on when the print process is started.

4.2 Software Toolkit

To support printing with ECPlotter, we provide a software toolkit that can be used by both non-experts and experts. The toolkit consists of an export script for Adobe Illustrator and a standalone application for generating the print file (gcode). The application can be used in two ways, one where the user loads their graphics, place them where they want it to be printed on the substrate and can then add connectors. Using this option provides enables the user to use the optimal settings found by selected whether the substrate is porous or non porous. The only other settings that are required for the user to know is the substrate dimensions. For advanced users, when designing a display in Illustrator the graphics for each ink type must be put in their own respective layers and exported into separate vector files. While this can be achieved manually for each layer, our script does it automatically. Our application converts the vector files by first extruding the vectors into 3D models at a specified height (0.1mm, 0.2mm and 0.3mm, respectively for the electrochromic, conductive and electrolyte layer). The increasing heights ensures the needle will not scratch or touch the underlying layer during printing. Toolpaths are generated based on the 3D models and extrusion rates are calculated

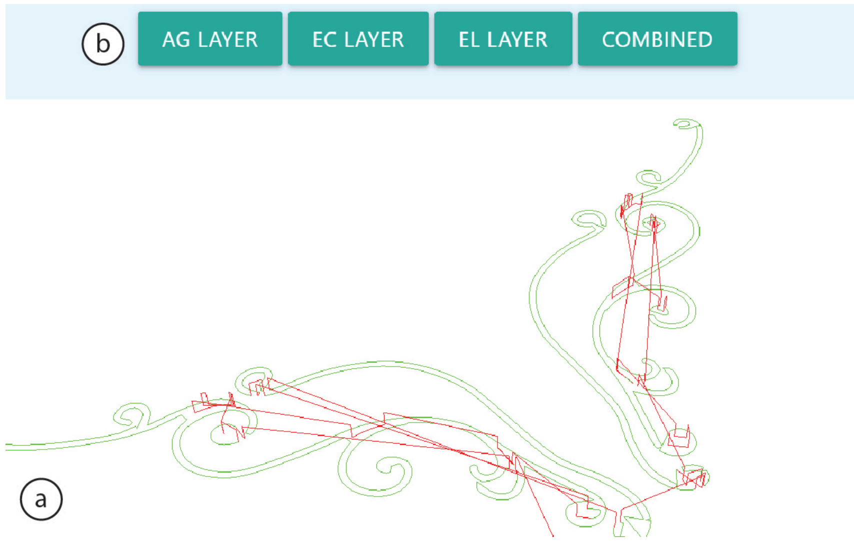

Fig. 8. After generating a print file, the software presents the user with: (a) a preview of the toolpath generated and (b) an option to select whether to preview the individual layers or the full print.

from the height of those models, the syringe diameter and tip diameter with a flow multiplier added to the calculation (Fig. 7, b). This process of converting the graphics files (svg), to .stl to .gcode is done automatically in the application. To support printing on different substrates the user can select the substrate thickness which controls at which height it deposits ink. (Fig. 7,a). Furthermore, the application allows the user to generate the separate gcode files per layer or a file with all the required printing instructions for a full display. Once printing instructions have been made a preview of the toolpaths is presented to the user (Fig. 8,a). This can help the user visualize how it will print the display and potentially spot errors.

The software, a hardware list with detailed instructions for assembly and wiring, as well as all needed files for 3D printing the custom parts will be made available under an open source license on acceptance of the paper.

4.3 Functional Inks

Using syringes to print gives the advantage of allowing a broad range of inks to be used in the printer without the restrictions typically seen using other printing methods. Ink-jet printing requires the ink to be highly liquid with nanoparticles to avoid clogging the printhead nozzles whereas silkscreen printing requires the ink to be more viscous and is not too restricted on particle sizes as the ink will be squeezed through a mesh. Syringe depositing can use inks at both ends of the spectrum. However, if the ink is too viscous the motor pushing the syringe plunger will not be able to apply enough force to push it out. Following is a description of the inks that we - through experimental testing - found to yield good results with ECPlotter.

Conductive ink: While there are many off-the-shelf solutions for conductive inks (e.g silver or copper nanoparticle ink), these are typically expensive (e.g., \$186 for 10g Silver nanoparticle ink [1] and \$300 for 5mL copper ink [2]). Because of this, we decided to mix our own conductive ink using inexpensive materials such as acrylic paint (\$10 for 1L),

[1]https://www.sigmaaldrich.com/US/en/product/aldrich/798738
[2]https://www.sigmaaldrich.com/US/en/product/aldrich/907413

nano graphite powder ($15 for 1L) and water. This allowed us to control the viscosity and resistance of the ink by changing the ratio between the different components. We mixed a range of different ratios starting with 1:2 (acrylic paint, graphite) by volume and after printing we measured the resistance on a 100mm by 2mm line with a height of 0.2mm on glass. Each line was oven dried at 100° for 3minutes before measuring the resistance. We found that a ratio of 2:5:2 (acrylic paint, graphite, water) had a viscosity that was not too liquid or too viscous with a resistance of 2.4kΩ. Furthermore, because we use acrylic paint and graphite for the ink we can cure it with lower temperatures (100°, 3min) than e.g. silver (150°, 30min) or copper (300°, 30min) solutions.

Electrochromic ink: We used off-the-shelf PEDOT:PSS ink solutions from Sigma Aldritch as this ink is not only electrochromic but also conductive. These inks are sold with different concentrations of PEDOT:PSS mixed in water where higher concentrations increases the conductivity but also the color vibrancy. We tested two solutions (0.8% and 5.0% PEDOT:PSS concentration) where the 0.8% solution is sold as an ink-jettable ink that also contains glycol and ethanol and the 5.0% concentration is sold as a screen printing solution. Our experience with the screen printable solution is that even with extensive stirring of the ink before filling a syringe, the resulting print exhibited small dots and inconsistencies. Furthermore to get as close to a consistent print as possible the needle tip had to slightly touch the substrate. While this is not a problem for hard surfaces such as glass or ceramics it poses a problem on paper and fabric as the tip has a chance to pull, scratch or destroy the substrate. The best results were found using the ink-jettable solution and printing with a low flow rate with the needle tip being between 0.05 to 0.1mm above the substrate.

Electrolyte: For the electrolytic layer we used electrolyte from Ynvisible as this has previously been reported [16] to be robust and in a gel form that can be syringe deposited. The electrolyte can be cured using UV light in the 365Nm range allowing us to use off-the-shelf flashlights for the curing pass.

4.4 Recommended Print Settings

Each layer has its own unique properties that the print settings must reflect. We first print the electrochromic layer as this requires the least amount of thickness, then on top of that we print the conductive layer and finally the electrolyte layer. This order also reflects the different thicknesses required by the layers. To find the optimal settings we first set the flow rate to 100% and tip diameter setting to the actual tip diameter and adjusted the print speed to a setting (15mm/s) that resulted in consistent depositing of material, we then printed a 10 by 10 grid of 10mm^2 squares with each square having a unique combination of tip diameter (0.1mm increments) and flow rate (5% increments). The reduced tip diameter in the settings ensures the needle will move over its own track as it prints the lines thereby creating a consistent ink field. This process was repeated with finer increments if needed. We selected the settings where there were no holes or visible ink lines in the printed fields while at same time there were not too much material deposited. In the following we will describe the settings we found to work best for each layer.

Electrochromic layer: As mentioned in the challenges section the electrochromic ink needs a very thin layer to ensure optimal contrast ratio. Too much ink and the color will be very vibrant but the contrast ratio will suffer. We print the layer using a 21-gauge (0.8mm) needle tip and depending on the substrate we use different settings. While using a smaller diameter needle tip would provide increased precision, we found that it was difficult to print consistent layers with any diameters below (0.8mm). For non-porous substrates (glass or ceramics) we set the tip diameter to 50% (0.4mm) of the actual needle and a flow rate of 25% - 30%. The reduced flow ensures minimal ink puddle build up as the ink is 99.2% water and being printed on a non-porous substrate. For porous substrates (paper and fabric) we use the same tip diameter setting but increase the flow rate to 35% - 40%. We found that porous substrates absorbs a bit of the ink during printing leaving visible print lines when printing with lower flow rates. Another option would be to lower the tip diameter setting even further making it print over previous lines more times and increasing the flow rate, however, this would increase the print duration.

Conductive layer: As we use PEDOT:PSS for the electrochromic layer, the purpose of the conductive layer is providing leads to the electrochromic fields. We print using a 19-gauge (1.0mm) needle tip on non-porous substrates and 18-gauge (1.2mm) on porous substrates. To provide the most consistent print of the conductive ink we set the tip diameter to 75% (0.8mm or 0.9mm). For non-porous substrates we found that using a flow rate of 105% provides enough ink without causing too much build up on the substrate. More than 105% results in excess ink being dragged along the surface and potentially into the electrochromic fields. On porous substrates we found that because the substrate absorbs a bit of the water the conductive ink dries faster and thus increasing the flow rate to 130% results in better consistency.

Electrolyte layer: The electrolyte layer is the most forgiving of the three in that the ink itself has a gel consistency and only needs to cover the electrochromic fields and connect those fields. We print this layer using a 14-gauge (2.0mm) needle tip and use a tip diameter setting of 80% (1.6mm) with a flow rate of 125%. The reduced tip diameter setting and the increased flow rate ensures that the lines of gel are connecting during printing and creates a consistent layer of electrolyte. Our tests showed that reducing the flow rate creates visible lines of electrolyte after printing. Even though the gel over time has the tendency to flatten out and connect with nearby printed lines this takes time and requires introducing pauses in the printing to allow for this to happen. By increasing the flow rate we can print the electrolyte and start the curing process directly after printing. This leads to a thicker electrolyte layer and if a thin display is required the previously mentioned process where pauses are introduced might be preferable. However, as one of the main goal of ECPlotter is to decrease the time between design iterations of electrochromic displays, we decided to sacrifice the thickness of the displays in favour of a fast process.

Substrate thickness: The substrate thickness setting is what allows the printer to print on different substrates as this offsets the heights otherwise used by each layer. We use the printer's own movement by commanding the printer to pick up one of the syringe tools and home the Z height. The printer is calibrated so that after homing, a height of 0 results in the needle tip slightly resting on the underlying glass bed we put our substrates on. By raising the height of the gantry and moving it over the substrate, we can lower the height in small increments. We then put a 0.05mm steel feeler between the substrate and the needle tip, similar to how the bed is calibrated on 3D printers. When a slight resistance can be felt on the steel feeler, we register the Z height on the printers screen and use that as the substrate thickness in the toolkit application. Using this method has proved to be the most reliable in finding the right thickness setting.

5 APPLICATION CASES

To demonstrate the toolkit's capabilities, we now present examples of displays printed using ECPlotter: an interactive ceramic tile, an electrochromic greeting card and electrochromic fabric.

5.1 Interactive Ceramic tiles

Printing on rigid substrates is impossible with ink-jet printing and can even be an issue for silkscreen printing. If for example the substrate area is smaller than the silkscreen this can lead to damages in the screen when the pressure is applied. However, this is no issues with ECPlotter and therefore we explored this possibility by printing on ceramic tiles. These also present a unique opportunity to make a large display by printing on individual tiles first and then grouping these together. With abstract graphical patterns similar to those seen for example in Portuguese tile design it would be possible to use the conductive traces to connect multiple tiles together. This would allow for an entire wall to

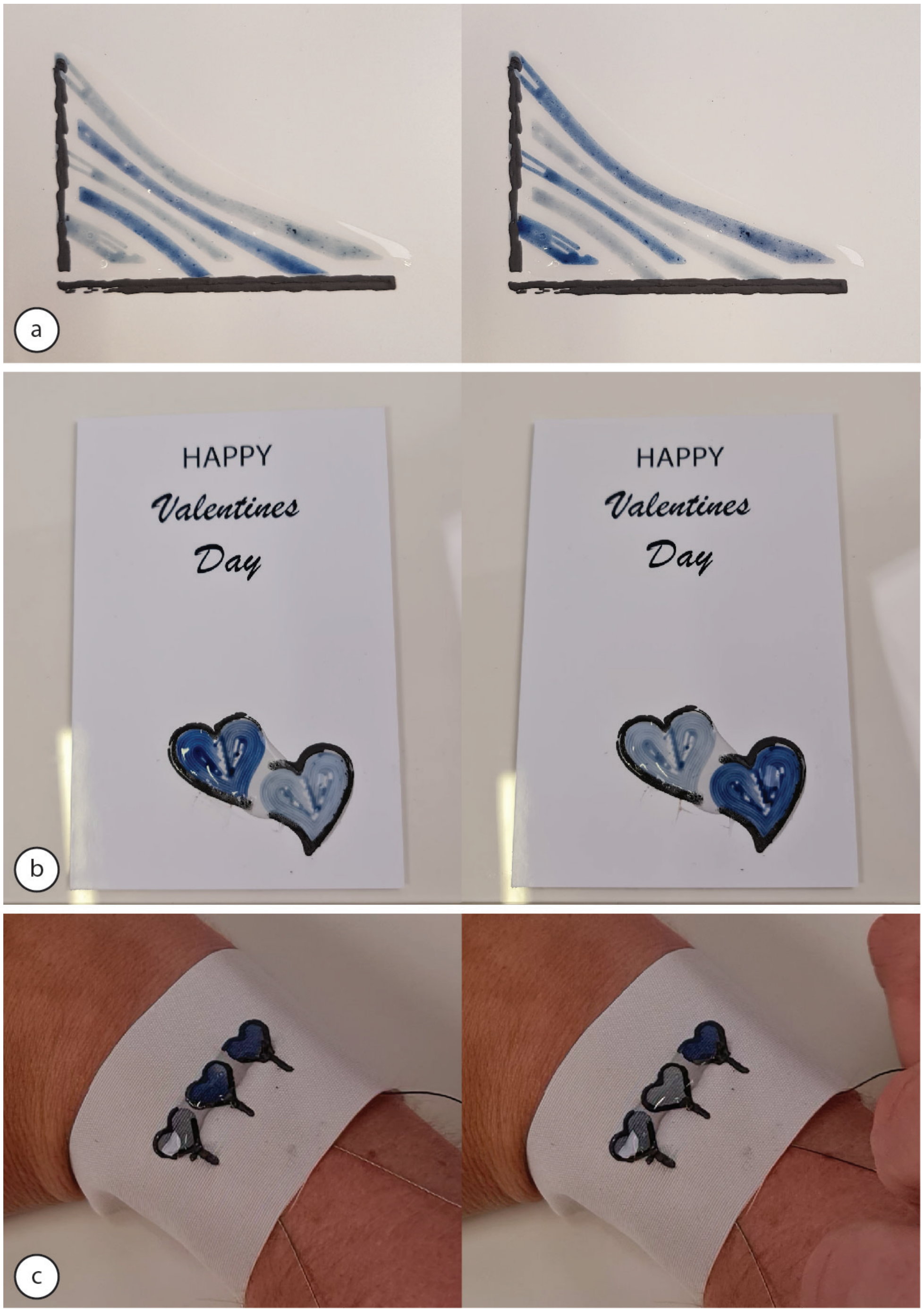

Fig. 9. Functional prototypes printed using ECPlotter: (a) a display printed on ceramic tile, (b) a display printed directly on photo paper and (c) a display printed on polyester fabric.

be interactive where the design could change near instantly or over a longer period of time and act as a decorative element [38]. In our first example (Fig. 9,a), we leverage the possibility of adjusting the height of ink depositing to print on a ceramic tile. Ceramic tile inherently does not have a completely flat surface due to shrinkage during the heating process when it is being fabricated. However, despite this, ECPlotter is able to print on a surface that has minor height differences. Our example shows that even though neither the conductive or electrochromic layer are perfectly printed and shows minor inconsistencies the display still functions and presents a vibrant change. The size of the print is 9cm by 7.5cm and took 45 minutes to print.

5.2 Electrochromic Greeting Card

In our second example we combine conventional ink-jet printing with ECPlotter by first printing a design onto photo paper using an ink-jet printer and thereafter placing it in ECPlotter to print the electrochromic display inks. While faux combination displays have been presented before by first fabricating a complete electrochromic display on transparent plastics and then sandwiching that on top of a piece of paper with print on it [16, 21], our method differs in that the paper itself becomes the substrate for the electrochromic display. This method of fabricating a display will enable designers to create graphics where smaller or larger parts are interactive. Our example shows this by integrating two interactive hearts into an otherwise static Valentine's greeting card (Fig. 9,b). The size of the print is 4cm by 6cm and took 55 minutes to print. Even though it is smaller in size than the ceramic tile example, due to the curved forms the printer has longer travelling paths that increase the printing time.

5.3 Electrochromic Fabric

Previous examples of creating electrochromic displays for wearables have used PET-ITO encapsulated electrochromic displays and stitched them into the fabric either by cutting out a hole in the fabric and stitching along the outline [15] or by creating a sandwich of fabric, display and fabric [17]. While these examples do present electrochromic displays in wearables there are a couple of issues with using a PET-ITO encapsulated display: first, when they are bent they are bent along one curve and cannot curl like fabric, second, the PET surface of the display has a high reflectancy which makes it stand out in combination with most fabrics and thereby they seem often to not truly be apart of it. Other examples of creating electrochromic fabric use a process of dying the entire fabric in electrochromic material thereby making it one consistent color that can change with electricity [27, 45]. Our example introduces a display printed directly on the fabric and use it as the substrate which allows the display to follow the natural curling of the fabric. We tried printing on 100% cotton and polyester and found that cotton absorbs up too much of the electrochromic ink and presents near to no visual change when power is applied. Polyester slowly absorbed the ink, leaving enough time for the printer to heat cure the layer before too much ink was absorbed. To ensure even visual change between the hearts printed in the example (Fig. 9,c), they are outlined by a 2mm conductive line with conductive thread sewn into the bottom part of the outline. For this example we split up the printing process, as we decided to do the heat curing of the conductive layer post sewing to increase the bond between the conductive ink and thread. Finally the electrolyte is applied. The size of the print is 3.5cm by 1.5cm and took 20 minutes to print.

6 LIMITATIONS AND FUTURE WORK

We first discuss how the ECPlotter has addressed the challenges listed in Section 3, then we present possible next steps for improving the toolkit as well as the limitations.

Challenges: The first challenge *(Deposit correct amount of electrochromic ink.)* was addressed by using syringe depositing with a linear stepper motor moving the syringe plunger which allows very precise depositing of material. The software that calculates the amount can be used to vary material deposition per material where materials that require more, such as electrolyte, can be deposited with the amount required and for materials that require very fine deposition can be programmed for that, such as electrochromic materials. The second challenge *(Even distribution of electrolyte.)* is addressed by the ability to finely control both the movement and the deposition of material which is a native part of both CNC and 3D printers which the ECPlotter is based on. The third challenge *(Find or develop low temperature curable conductive ink.)* was addressed by developing our own low-cost conductive ink based on graphite, as opposed to buying relatively expensive copper or silver pastes. By developing the ink specifically for ECPlotter we ensure that it provides the most optimal viscosity and resistance and also enable remixing or mixing with different ratios for different purposes e.g. larger needle tips might require more viscous ink. The fourth and final challenge *(Find substrate(s) with minimal impairment of visual quality.)* was addressed by printing on a range of substrates from paper to ceramic. We found that the optimal solution for substrate is having a white or bright color so the visual change in the electrochromic material is more visible. However, some of the substrates printed on, came with their own issues as will be addressed in the following sections.

Display Quality: While the toolkit can print functional electrochromic displays, their visual quality is lower than what can be potentially achieved using silkscreen printing. This is mostly due to the difficulty of printing as little electrochromic ink as possible whilst also ensuring that the resulting printed electrochromic field have visual consistency and not damaging the substrate. This difficulty is clearly evident in the electrochromic greeting card example (Fig. 9, b) where the individual lines are visible due to the paper absorbing some of the ink during printing. As the electrochromic ink used for printing is highly liquid it is difficult to control its flow out of the needle tip. Possible solutions to solve this would be to use a more viscous PEDOT:PSS solution which would reduce the potential absorption of the paper. However, despite this, we believe the quality is sufficient for rapid prototyping of designs and displays when taking the fabrication time into account. Previous methods would require at minimum several hours and more manual labor before a design could be fabricated into a functional display whereas our toolkit can do so with minimal manual labor and in less than an hour, depending on the size of the display.

Additional Tools and Ink types: One advantage of using tool changing and syringe depositing is the ability to print a wide range of inks and adding extra features. In our current implementation we only use the necessary inks and tools to print a functional co-planar display. However, with added inks the toolkit would be able to print more complex designs. An example of this could be to add PVP (polyvinylpyrrolidone) ink that functions as an electronic insulator and thereby adding the ability to print conductive lines that cross each other if PVP is printed between the layers as seen done in Soft Inkjet Circuits [26]. Furthermore, adding e.g. a laser tool would enable not only engraving graphics or cutting the substrate but also printing silver conductive ink and cure it using an unfocused lens as presented in LaserFactory [41]. Furthermore, the way the toolkit is currently implemented it should be possible to easily adapt it with a completely different set of inks for a different purpose such as printing electrolumiscent displays [44].

Multiple syringe sizes: The syringe depositing tools currently only supports 1mL syringes with an outer diameter of 6.8mm which limits the exchangeability with other types of syringes. This is not a problem when printing smaller displays as the amount of material required for these sizes are minimal, however, when printing bigger displays, the amount of e.g. electrolyte required can easily reach more than 1mL. Future designs of the syringe depositing tool should be able to handle multiple sizes of syringes and thereby alleviating this limitation. Another option would be to introduce a refilling step in the software, where the printing process would be stopped and would allow the user to refill the syringe. This would also allow for printing large scale designs, e.g. on a full A4 sheet.

Variable height printing: The current iteration of the toolkit can only print a flat display on substrates up to a thickness of 4cm as it does not have an internal sensor for registering the needle offset from the substrate surface. With a more advanced syringe depositing tool with builtin height measuring capabilities, e.g. by attaching a laser distance sensor, it would be possible to print on surfaces with curvatures such as relief prints or low 3D models. This opens the possibility of creating more advanced electrochromic displays that are integrated into non-planar products. An example could be interactive facemasks or architectural models.

7 CONCLUSION

In this paper, we presented ECPlotter, a toolkit that can rapidly print prototypes of electrochromic displays. We presented the structural challenges of electrochromic displays and what to take into account when printing such a display. We lay out the hardware of the toolkit and its tool changing which enables printing a full display in one process, and the software which translates designs into printer specific instructions. We follow this up by presenting the inks we found to work best with this printing method and the recommended settings to ensure a consistent and functional display prototype. We showed the printers capabilities by presenting displays printed on ceramic tile, photo paper and fabric. While in this work we focused exclusively on electrochromic displays, the presented hardware and software toolkit is also able to print other inks with higher viscosity - that might not be ink-jet printable - thereby enabling other researchers to make use of the multi-tool printing for their purposes. For future work, we aim to add more ink and tool types to increase the complexity and range of displays that can be printed, redesign the syringe depositing tool to allow for more larger syringes which increases the possible print size and adding a height sensor to the syringe depositor tool to allow for printing on non-planar substrates.

ACKNOWLEDGMENTS

We would like to thank Stefanie Mueller and Michael Wessely as well as the whole HCI Engineering Group, at CSAIL, MIT for their big support and comments on this paper. This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 760973.

REFERENCES

[1] P. Andersson, R. Forchheimer, P. Tehrani, and M. Berggren. 2007. Printable All-Organic Electrochromic Active-Matrix Displays. *Advanced Functional Materials* 17, 16 (Nov. 2007), 3074–3082. https://doi.org/10.1002/adfm.200601241

[2] Nivedita Arora, Ali Mirzazadeh, Injoo Moon, Charles Ramey, Yuhui Zhao, Daniela C. Rodriguez, Gregory D. Abowd, and Thad E. Starner. 2021. MARS: Nano-Power Battery-free Wireless Interfaces for Touch, Swipe and Speech Input. *arXiv:2108.09011 [cs]* (Aug. 2021). https://doi.org/10.1145/3472749.3474823 arXiv: 2108.09011.

[3] James P. Coleman, Anne T. Lynch, Puttanachetty Madhukar, and John H. Wagenknecht. 1999. Printed, flexible electrochromic displays using interdigitated electrodes. *Solar Energy Materials and Solar Cells* 56, 3-4 (Jan. 1999), 395–418. https://doi.org/10.1016/S0927-0248(98)00144-5

[4] Ashley Colley, Caglar Genc, Markus Löchtefeld, Heiko Mueller, Walther Jensen, and Jonna Häkkilä. 2021. Exploring Button Design for Low Contrast User Interfaces. In *Human-Computer Interaction – INTERACT 2021*, Carmelo Ardito, Rosa Lanzilotti, Alessio Malizia, Helen Petrie, Antonio Piccinno, Giuseppe Desolda, and Kori Inkpen (Eds.). Vol. 12936. Springer International Publishing, Cham, 411–415. https://doi.org/10.1007/978-3-030-85607-6_48 Series Title: Lecture Notes in Computer Science.

[5] Caglar Genc, Ashley Colley, Markus Löchtefeld, and Jonna Häkkilä. 2020. Face mask design to mitigate facial expression occlusion. In *Proceedings of the 2020 International Symposium on Wearable Computers*. ACM, Virtual Event Mexico, 40–44. https://doi.org/10.1145/3410531.3414303

[6] Gilad Gome, Julian Waksberg, Andrey Grishko, Iddo Yehoshua Wald, and Oren Zuckerman. 2019. OpenLH: Open Liquid-Handling System for Creative Experimentation with Biology. In *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction*. ACM, Tempe Arizona USA, 55–64. https://doi.org/10.1145/3294109.3295619

[7] Nan-Wei Gong, Steve Hodges, and Joseph A. Paradiso. 2011. Leveraging conductive inkjet technology to build a scalable and versatile surface for ubiquitous sensing. In *Proceedings of the 13th international conference on Ubiquitous computing - UbiComp '11*. ACM Press, Beijing, China, 45. https://doi.org/10.1145/2030112.2030120

[8] C.G. Granqvist, M.A. Arvizu, I. Bayrak Pehlivan, H.Y. Qu, R.T. Wen, and G.A. Niklasson. 2018. Electrochromic materials and devices for energy efficiency and human comfort in buildings: A critical review. *Electrochimica Acta* 259 (Jan. 2018), 1170–1182. https://doi.org/10.1016/j.electacta.2017.11.169

[9] Daniel Groeger and Jürgen Steimle. 2018. ObjectSkin: Augmenting Everyday Objects with Hydroprinted Touch Sensors and Displays. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 1, 4 (Jan. 2018), 1–23. https://doi.org/10.1145/3161165

[10] Ollie Hanton, Michael Wessely, Stefanie Mueller, Mike Fraser, and Anne Roudaut. 2020. ProtoSpray: Combining 3D Printing and Spraying to Create Interactive Displays with Arbitrary Shapes. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. ACM, Honolulu HI USA, 1–13. https://doi.org/10.1145/3313831.3376543

[11] Nhayoung Hong, Gi-Hoon Yang, JaeHwan Lee, and GeunHyung Kim. 2018. 3D bioprinting and its *in vivo* applications: 3D BIOPRINTING AND ITS *IN VIVO* APPLICATIONS. *Journal of Biomedical Materials Research Part B: Applied Biomaterials* 106, 1 (Jan. 2018), 444–459. https://doi.org/10.1002/jbm.b.33826

[12] Kohei Ikeda, Naoya Koizumi, and Takeshi Naemura. 2018. FunCushion: Fabricating Functional Cushion Interfaces with Fluorescent-Pattern Displays. In *Advances in Computer Entertainment Technology*, Adrian David Cheok, Masahiko Inami, and Teresa Romão (Eds.). Vol. 10714. Springer International Publishing, Cham, 470–487. https://doi.org/10.1007/978-3-319-76270-8_33

[13] Giuseppina Iuliano, Antonio Rosato, Sergio Sibilio, Michelangelo Scorpio, Giuseppe Peter Vanoli, and Filippo de Rossi. 2016. Electrochromic windows: state of art and future developments. In *16th CIRIAF National Congress*. Morlacchi Editore, Assisi, Italy, COD 103.

[14] Artem Ivanov and Maximilian Wurzer. 2017. Integration of screen-printed electroluminescent matrix displays in smart textile items — Implementation and evaluation. In *2017 21st European Microelectronics and Packaging Conference (EMPC) & Exhibition*. IEEE, Warsaw, 1–6. https://doi.org/10.23919/EMPC.2017.8346873

[15] Pradthana Jarusriboonchai, Emmi Harjuniemi, Heiko Müller, Ashley Colley, and Jonna Häkkilä. 2019. Linn dress: enabling a dynamically adjustable neckline. In *Proceedings of the 23rd International Symposium on Wearable Computers*. ACM, London United Kingdom, 274–278. https://doi.org/10.1145/3341163.3346934

[16] Walther Jensen, Ashley Colley, Jonna Häkkilä, Carlos Pinheiro, and Markus Löchtefeld. 2019. TransPrint: A Method for Fabricating Flexible Transparent Free-Form Displays. *Advances in Human-Computer Interaction* 2019 (May 2019), 1–14. https://doi.org/10.1155/2019/1340182

[17] Walther Jensen, Ashley Colley, and Markus Löchtefeld. 2019. VitaBoot: footwear with dynamic graphical patterning. In *Proceedings of the 23rd International Symposium on Wearable Computers - ISWC '19*. ACM Press, London, United Kingdom, 279–283. https://doi.org/10.1145/3341163.3346937

[18] Walther Jensen, Brock Craft, Markus Löchtefeld, and Pernille Bjørn. 2022. Learning through interactive artifacts: Personal fabrication using electrochromic displays to remember Atari women programmers. *Entertainment Computing* 40 (Jan. 2022), 100464. https://doi.org/10.1016/j.entcom.2021.100464

[19] Walther Jensen, Hendrik Knoche, and Markus Löchtefeld. 2020. "Do you think it is going to be the cock?": using ambient shadow projection in dialogic reading. In *Proceedings of the 9TH ACM International Symposium on Pervasive Displays*. ACM, Manchester United Kingdom, 97–103. https://doi.org/10.1145/3393712.3395342

[20] Walther Jensen, Markus Löchtefeld, and Hendrik Knoche. 2019. ShadowLamp: An Ambient Display with Controllable Shadow Projection using Electrochromic Materials.. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems - CHI EA '19*. ACM Press, Glasgow, Scotland Uk, 1–6. https://doi.org/10.1145/3290607.3313011

[21] Walther Jensen, Thomas Streubel Kristensen, Christoffer Sand Kirk, Hassan Abdul Hameed, Daniel Bergmann Villadsen, and Markus Löchtefeld. 2020. Hybrid Settlers - Integrating Dynamic Tiles into a Physical Board Game using Electrochromic Displays. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems*. ACM, Honolulu HI USA, 1–7. https://doi.org/10.1145/3334480.3382857

[22] Yuhua Jin, Isabel Qamar, Michael Wessely, and Stefanie Mueller. 2020. Photo-Chromeleon: Re-Programmable Multi-Color Textures Using Photochromic Dyes. In *ACM SIGGRAPH 2020 Emerging Technologies*. ACM, Virtual Event USA, 1–2. https://doi.org/10.1145/3388534.3407296

[23] Cagdas Karatas and Marco Gruteser. 2015. Printing multi-key touch interfaces. In *Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing - UbiComp '15*. ACM Press, Osaka, Japan, 169–179. https://doi.org/10.1145/2750858.2804285

[24] Kunihiro Kato, Hiroki Ishizuka, Hiroyuki Kajimoto, and Homei Miyashita. 2018. Double-sided Printed Tactile Display with Electro Stimuli and Electrostatic Forces and its Assessment. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, Montreal QC Canada, 1–12. https://doi.org/10.1145/3173574.3174024

[25] Yoshihiro Kawahara, Steve Hodges, Benjamin S. Cook, Cheng Zhang, and Gregory D. Abowd. 2013. Instant inkjet circuits: lab-based inkjet printing to support rapid prototyping of UbiComp devices. In *Proceedings of the 2013 ACM international joint conference on Pervasive and ubiquitous computing*. ACM, Zurich Switzerland, 363–372. https://doi.org/10.1145/2493432.2493486

[26] Arshad Khan, Joan Sol Roo, Tobias Kraus, and Jürgen Steimle. 2019. Soft Inkjet Circuits: Rapid Multi-Material Fabrication of Soft Circuits using a Commodity Inkjet Printer. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. ACM, New Orleans LA USA, 341–354. https://doi.org/10.1145/3332165.3347892

[27] Whitney M Kline, Robert G Lorenzini, and Gregory A Sotzing. 2014. A review of organic electrochromic fabric devices. *Coloration Technology* 130, 2 (April 2014), 73–80. https://doi.org/10.1111/cote.12079

[28] Benjamin A. E. Lehner, Dominik T. Schmieden, and Anne S. Meyer. 2017. A Straightforward Approach for 3D Bacterial Printing. *ACS Synthetic Biology* 6, 7 (July 2017), 1124–1130. https://doi.org/10.1021/acssynbio.6b00395

[29] Jennifer A. Lewis. 2006. Direct Ink Writing of 3D Functional Materials. *Advanced Functional Materials* 16, 17 (Nov. 2006), 2193–2204. https://doi.org/10.1002/adfm.200600434

[30] Markus Lochtefeld, Anna Dagmar Bille Milthers, and Timothy Merritt. 2021. Staging Constructionist Learning about Energy for Children with Electrochromic Displays and Low-Cost Materials. In *20th International Conference on Mobile and Ubiquitous Multimedia*. ACM, Leuven Belgium, 73–83. https://doi.org/10.1145/3490632.3490654

[31] Markus Lochtefeld, Walther Jensen, and Caglar Genc. 2021. Prototyping of Transparent and Flexible Electrochromic Displays. In *20th International Conference on Mobile and Ubiquitous Multimedia*. ACM, Leuven Belgium, 179–181. https://doi.org/10.1145/3490632.3497750

[32] Markus Löchtefeld, Walther Jensen, Heiko Müller, and Ashley Colley. 2019. Prototyping Transparent and Flexible Electrochromic Displays. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems - CHI EA '19*. ACM Press, Glasgow, Scotland Uk, 1–4. https://doi.org/10.1145/3290607.3298827

[33] 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*. ACM, Glasgow Scotland Uk, 1–10. https://doi.org/10.1145/3290605.3300862

[34] Bille Milthers, Anna Dagmar, and Markus Lochtefeld. 2021. ChromaBot - Prototyping Soft Robotic Actuators with Integrated Electrochromic Displays. In *20th International Conference on Mobile and Ubiquitous Multimedia*. ACM, Leuven Belgium, 198–200. https://doi.org/10.1145/3490632.3497831

[35] Christos Mourouzi, Isabel P. S. Qamar, and Anne Roudaut. 2018. SweepScreen: Sweeping Programmable Surfaces to Create Low-fi Displays Everywhere. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, Montreal QC Canada, 1–6. https://doi.org/10.1145/3170427.3188462

[36] Heiko Müller, Ashley Colley, Jonna Häkkilä, Walther Jensen, and Markus Löchtefeld. 2019. Using electrochromic displays to display ambient information and notifications. In *Adjunct Proceedings of the 2019 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2019 ACM International Symposium on Wearable Computers*. ACM, London United Kingdom, 1075–1078. https://doi.org/10.1145/3341162.3344844

[37] Heiko Müller, Emma Napari, Lauri Hakala, Ashley Colley, and Jonna Häkkilä. 2019. Running shoe with integrated electrochromic displays. In *Proceedings of the 8th ACM International Symposium on Pervasive Displays - PerDis '19*. ACM Press, Palermo, Italy, 1–2. https://doi.org/10.1145/3321335.3329686

[38] Sara Nabil and David Kirk. 2021. Decoraction: a Catalogue for Interactive Home Decor of the Nearest-Future. In *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction*. ACM, Salzburg Austria, 1–13. https://doi.org/10.1145/3430524.3446074

[39] Steven Nagels, Raf Ramakers, Kris Luyten, and Wim Deferme. 2018. Silicone Devices: A Scalable DIY Approach for Fabricating Self-Contained Multi-Layered Soft Circuits using Microfluidics. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, Montreal QC Canada, 1–13. https://doi.org/10.1145/3173574.3173762

[40] Yoshihisa Naijoh, Tohru Yashiro, Shigenobu Hirano, Yoshinori Okada, SukChan Kim, Kazuaki Tsuji, Hiroyuki Takahashi, Koh Fujimura, and Hitoshi Kondoh. 2011. Multi-layered electrochromic display. In *IDW*, Vol. 11. 375–378.

[41] 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*. ACM, Yokohama Japan, 1–15. https://doi.org/10.1145/3411764.3445692

[42] Simon Olberding, Nan-Wei Gong, John Tiab, Joseph A. Paradiso, and Jürgen Steimle. 2013. A cuttable multi-touch sensor. In *Proceedings of the 26th annual ACM symposium on User interface software and technology*. ACM, St. Andrews Scotland, United Kingdom, 245–254. https://doi.org/10.1145/2501988.2502048

[43] Simon Olberding, Sergio Soto Ortega, Klaus Hildebrandt, and Jürgen Steimle. 2015. Foldio: Digital Fabrication of Interactive and Shape-Changing Objects With Foldable Printed Electronics. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*. ACM, Charlotte NC USA, 223–232. https://doi.org/10.1145/2807442.2807494

[44] Simon Olberding, Michael Wessely, and Jürgen Steimle. 2014. PrintScreen: fabricating highly customizable thin-film touch-displays. In *Proceedings of the 27th annual ACM symposium on User interface software and technology*. ACM, Honolulu Hawaii USA, 281–290. https://doi.org/10.1145/2642918.2647413

[45] Heloisa Ramlow, Karina Luzia Andrade, and Ana Paula Serafini Immich. 2021. Smart textiles: an overview of recent progress on chromic textiles. *The Journal of The Textile Institute* 112, 1 (Jan. 2021), 152–171. https://doi.org/10.1080/00405000.2020.1785071

[46] Daniel Saakes, Masahiko Inami, Takeo Igarashi, Naoya Koizumi, and Ramesh Raskar. 2012. Shader printer. In *ACM SIGGRAPH 2012 Emerging Technologies on - SIGGRAPH '12*. ACM Press, Los Angeles, California, 1–1. https://doi.org/10.1145/2343456.2343474

[47] David Sweeney, Nicholas Chen, Steve Hodges, and Tobias Grosse-Puppendahl. 2016. Displays as a Material: A Route to Making Displays More Pervasive. *IEEE Pervasive Computing* 15, 3 (July 2016), 77–82. https://doi.org/10.1109/MPRV.2016.56

[48] Orkan Telhan, Federico Casalegno, Juhong Park, Sotirios Kotsopoulos, and Carl Yu. 2010. Interaction design with building facades. In *Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction - TEI '10*. ACM Press, Cambridge, Massachusetts, USA, 291. https://doi.org/10.1145/1709886.1709948

[49] Dhaval Vyas, Wim Poelman, Anton Nijholt, and Arnout De Bruijn. 2012. Smart material interfaces: a new form of physical interaction. In *CHI '12 Extended Abstracts on Human Factors in Computing Systems*. ACM, Austin Texas USA, 1721–1726. https://doi.org/10.1145/2212776.2223699

[50] Guanyun Wang, Lining Yao, Wen Wang, Jifei Ou, Chin-Yi Cheng, and Hiroshi Ishii. 2016. xPrint: A Modularized Liquid Printer for Smart Materials Deposition. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, San Jose California USA, 5743–5752. https://doi.org/10.1145/2858036.2858281

[51] Martin Weigel, Aditya Shekhar Nittala, Alex Olwal, and Jürgen Steimle. 2017. SkinMarks: Enabling Interactions on Body Landmarks Using Conformal Skin Electronics. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, Denver Colorado USA, 3095–3105. https://doi.org/10.1145/3025453.3025704

[52] Mark Weiser. 1999. The Computer for the 21st Century. *SIGMOBILE Mob. Comput. Commun. Rev.* 3, 3 (July 1999), 3–11. https://doi.org/10.1145/329124.329126

[53] Michael Wessely, Ticha Sethapakdi, Carlos Castillo, Jackson C. Snowden, Ollie Hanton, Isabel P. S. Qamar, Mike Fraser, Anne Roudaut, and Stefanie Mueller. 2020. Sprayable User Interfaces: Prototyping Large-Scale Interactive Surfaces with Sensors and Displays. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. ACM, Honolulu HI USA, 1–12. https://doi.org/10.1145/3313831.3376249

[54] Michael Wessely, Theophanis Tsandilas, and Wendy E. Mackay. 2016. Stretchis: Fabricating Highly Stretchable User Interfaces. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. ACM, Tokyo Japan, 697–704. https://doi.org/10.1145/2984511.2984521

[55] Dingtian Zhang, Jung Wook Park, Yang Zhang, Yuhui Zhao, Yiyang Wang, Yunzhi Li, Tanvi Bhagwat, Wen-Fang Chou, Xiaojia Jia, Bernard Kippelen, Canek Fuentes-Hernandez, Thad Starner, and Gregory D. Abowd. 2020. OptoSense: Towards Ubiquitous Self-Powered Ambient Light Sensing Surfaces. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 4, 3 (Sept. 2020), 1–27. https://doi.org/10.1145/3411826