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TOWARDS DEMOCRATIZING THE FABRICATION OF ELECTROCHROMIC DISPLAYS

BY
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AALBORG UNIVERSITY
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Towards Democratizing the Fabrication of Electrochromic Displays

Ph.D. Dissertation by

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Curriculum Vitae

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2013	Graduated B.Sc in Medialogy at School of Information & Communication Technology, Aalborg University
2013 - 2015	Laboratory Engineer at The Department of Architecture, Design & Media Technology, Aalborg University Researched and developed vibrotactile garments, interactive furniture and urban art installations as part of the CultAR EU Project [1].
2017	Graduated M.Sc in Medialogy with a specialization in Interaction Design at School of Information & Communication Technology, Aalborg University Master Thesis title: See me, See me - An Exploration in When and How Drones should Acknowledge a Nearby Person
2017 - 2018	Research Assistant at The Department of Architecture, Design & Media Technology, Aalborg University
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[1] `https://cordis.europa.eu/project/id/601139`

Abstract

This thesis aims at developing new fabrication methods for non-light emitting displays that are flexible, low-powered and transparent moving towards democratizing the fabrication. However, to further democratize the fabrication and enable more widespread access to the technology, examples of what it is capable of is required for inspiration. Therefore, the thesis also aims at developing application scenarios for electrochromic displays.

The first fabrication method presented use off-the-shelf, inexpensive and readily available hardware and is presented along with best practice guides for producing good quality electrochromic display prototypes. This method has been used extensively throughout the thesis period in both workshops and to produce the prototypes presented for the application scenarios. The second fabrication method presented use a custom electrochromic display printer that reduce the manual labour and time it takes to fabricate an electrochromic display thereby improving iteration times during prototyping. Thirdly, while not successful, research and findings are presented in attempting to develop an ink-jet fabrication method where consumer printers are used to print the conductive and electrochromic materials.

Because the display technology is different from regular well-known technologies, application scenarios are presented to inspire and help those interested generating ideas for what it can be used for. A study is presented where undergrad students had to create a physical artifact during a week-long workshop in a Makerspace. Electrochromic displays were required for adding interactivity to the artifacts. This study shows that the methods developed for fabricating electrochromic displays can be used in teaching environments. A lamp prototype that use the transparency of electrochromic displays to cast changing shadows is presented. This is an example of how, by changing shadows, the look, feel and mood of a room can be changed interactively. A shoe prototype with an integrated electrochromic display as part of the shoe is presented and shows how the flexibility enable embedding into fabrics. And, finally an example of how custom shapes electrochromic displays can be used in traditionally static board games can be used to add changing game states to a game. Each of these examples show different aspects of how electrochromic displays can be utilized which should help increase ideas for those who wish to work with the technology. The hope is, that by democratizing the fabrication through the methods and example scenarios, there will be more inclusion of the technology.

Resumé

Formålet med denne Ph.d.-afhandling er at udvikle nye fabrikations metoder til skærme der ikke udsender lys, er fleksible, bruger lav strøm, er gennemsigtige, og derved flytte fabrikationen mod at blive demokratiseret. For at yderligere demokratisere fabrikationen og tillade mere udspredt tilgang til teknologien, er det nødvendigt med eksempler der viser hvad teknologien kan, for at øge inspiration. Derfor søger afhandlingen også at udvikle anvendelsesscenarier for elektrokromiske skærme.

Den første fabrikations metode præsenteret bruger billige og let tilgængelige hyldevarer og er præsenteret sammen med praktiske guides til fabrikation af elektrokromiske skærm prototyper af god kvalitet. Denne metode har været omfattende brugt gennem afhandlingsperioden i både seminarer og til at fremstille applikationsscenarie prototyperne. Den anden fabrikations metode præsenteret bruger en speciel printer der er designet og udviklet under afhandlingen til at fabrikere elektrokromiske skærme. Printeren reducerer mængden af manuelt arbejde og tiden det tager at fabrikere en elektrokromisk skærm, og derved forbedrer iterationstiden når der laves prototyper. For det tredje, selvom det ikke er lykkedes, er forskning og resultater præsenteret i et forsøg på at udvikle en ink-jet baseret fabrikations metode hvor forbruger printere er brugt til at printe ledende og elektrokromiske materialer.

Fordi skærm teknologien er anderledes end andre velkendte teknologier, er applikationsscenarier præsenteret for at inspirere og hjælpe interesserede udvikle ideer til hvad teknologien kan bruges til. Et studie er præsenteret hvor bachelor studerende skulle skabe et fysisk artefakt i løbet af en uge langt seminar i et Makerspace. Elektrokromiske skærme var påkrævet for at skabe interaktion i artefakterne. Dette studie viser at fabrikationsmetoderne udviklet kan bruges i læringsmiljøer. En lampe prototype er udviklet og præsenteret, der viser hvordan gennemsigtigheden af elektrokromiske skærme kan bruges til at projektere skiftende skygger. Dette er et eksempel på at udseendet, følelsen og humøret i et rum kan ændres interaktivt ved at skifte skyggerne i rummet. En sko prototype med en elektrokromisk skærm integreret er udviklet og præsenteret, hvilket viser hvordan fleksibiliteten af teknologien tillader integration i stof. Sidst, er et eksempel præsenteret hvor skærme med tilpasset form kan bruges i traditionelle brætspil til at ændre spiltilstand under et spil. Hver af disse eksempler viser forskellige aspekter af hvordan elektrokromiske skærme kan bruges, hvilket skulle hjælpe med at øge mængden af ideer hos dem der er interesseret i at arbejde med teknologien. Håbet er at ved at demokratisere fabrikationen gennem metoderne og applikationsscenarierne præsenteret, så vil teknologien blive mere inkluderet i fremtiden.

List of publications

The main body of the thesis consists of the following paper, divided by research area:

Fabricating Electrochromic Displays

[A] W. Jensen, A. Colley, J. Häkkilä, C. Pinheiro, and M. Löchtefeld, "TransPrint: A Method for Fabricating Flexible Transparent Free-Form Displays," *Advances in Human-Computer Interaction*, vol. 2019, pp. 1–14, May 2019.

[B] W. Jansen and M.Löchtefeld, "ECPlotter: A Toolkit for Rapid Prototyping of Electrochromic Displays", Submitted to *21st International Conference on Mobile and Ubiquitous Multimedia (MUM 2022)*.

Application Scenarios

[C] W. Jensen, B. Craft, M. Löchtefeld, and P. Bjørn, "Learning through interactive artifacts: Personal fabrication using electrochromic displays to remember Atari women programmers," *Entertainment Computing*, vol. 40, p. 100464, Jan. 2022.

[D] W. Jensen, M. Löchtefeld, and H. Knoche, "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*. Glasgow, Scotland Uk: ACM Press, 2019, pp. 1–6.

[E] W. Jensen, H. Knoche, and M. Löchtefeld, ""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*. Manchester United Kingdom: ACM, Jun. 2020, pp. 97–103

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[G] W. Jensen, T. Streubel Kristensen, C. Sand Kirk, H. A. Hameed, D. Bergmann Vil- ladsen, and M. Löchtefeld, “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*. Honolulu HI USA: ACM, Apr. 2020, pp. 1–7.

The following papers have been published during the Ph.D. study but are not included as part of the thesis:

[1] P. Zdziarska, F. A. Epp, W. Jensen, M. D. Gross, and E. Y.-L. Do, “Hooze: A Kinetic Fashion Accessory for Touch and Play,” in *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction*. Tempe Arizona USA: ACM, Mar. 2019, pp. 407–413.

[2] 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* (*UbiComp/ISWC '19 Adjunct*). Association for Computing Machinery, New York, NY, USA, 1075–1078.

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Contents

Preface

This thesis is a collection of papers in partial fulfillment of a PhD study at the Department of Architecture, Design and Media Technology, Aalborg University, Denmark. There are four chapters to the thesis. First, an introduction to the subjects of the thesis as well as its structure and scope. Second, a chapter on the state of the art. Third, a chapter on fabricating electrochromic displays including a section on work that failed and thus was not published. Finally the fourth chapter contains examples of application scenarios.

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I would like to thank my supervisor Markus Löchtefeld for always having my back, providing good supervision and almost always being up for a Friday beer. He was there through my bitchy phases and pushes my in the right direction when I faltered.

Walther Jensen
Aalborg University, September 16, 2022

Part I

Thesis

"The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it."

- Mark Weiser [13]

Chapter 1

Introduction

As of writing this thesis, it has been slightly over 30 years since Mark Weiser wrote his piece *Computer of the 21st Century* for Scientific America in which he laid the foundation for the field of Ubiquitous Computing [13]. In his piece he describes how when computing technologies can become small enough they can blend into our daily lives and through this we stop being consciously aware of it. One important building block for the Ubiquitous Computing field is smart materials which can be manipulated in a reversible and controlled way; and they are an important factor in making technology that blends into everyday life [4]. Since Mark Weiser's piece, research in smart materials and printed electronics have increased substantially as technologies such as printers, inks and electronics have improved. At the same time the cost and knowledge required to enter these fields have been significantly lowered. Today, if someone wants to build an interactive prototype there is no longer a need for expertise knowledge in electronics and programming [12]. Prototyping boards from the Arduino and Raspberry Pi organizations are readily available at a reasonable price with vast online communities and tutorials that enable easy entry into the fields of electronics [6, 10]. Even for the field of wearable computing these organizations provide prototyping systems that integrate easily into wearable technologies where instead of soldering, sewing conductive thread can be used to create electronic connection [1]. Besides these developments on the electronics side, we also saw significant changes on the side of physical fabrication. In 2005 Adrian Bowyer developed the RepRap 3D printer, an open source self replicating 3D printer [9]. Prior to this, 3D printers were available commercially only at a high entry price that most consumers could not afford. Due to the open source nature of the RepRap project the entire field of 3D printing has seen a drastic increase in both companies selling printers at a price that is available to most, in variations of what can be printed and in hobbyists using 3D printers to create prints for architecture, tabletop characters and functional models to mention a few. These developments gave way to the field that is known as Personal Fabrication (see Chapter 2).

Fig. 1.1: Examples of electrochromic devices. Left example shows the flexibility of the technology (Paper A) [8]. Right example shows how the transparency of electrochromic devices can work in combination with traditionally printed graphics. The snowflakes and text is part of the electrochromic device whereas the Santa, reindeer and DecoChrom logo is inkjet printed on normal paper and placed underneath.

Common for these technologies is that they have been democratized which means access to the technologies has become increasingly more accessible to people through improved user experiences, availability, and low cost [7]. And through this increased access each technology has seen an increase in the range of applications they have been used for. Along with this, display technologies has also seen a similar trajectory with small LCD and OLED screens becoming available at reasonable prices. However, there are a few restrictions with these display technologies, for one they are mostly only available in rectangular shapes, are rigid and light-emitting which can make them difficult to blend into other materials. Furthermore, there are also problems associated with adding more light emitting technology in our daily lives as sleep patterns are being disrupted which has increased sleep deficiency in people [3]. While products such as smart phones and tablets, have included night time modes filtering out the blue light which disturbs sleep, the effectiveness of this is debatable [11].

One display technology that has aimed at removing the light emissions is electronic ink (E-Ink) which consists of an rectangular array of very small capsules (pixels) that can be either black or white and by controlling these pixels it functions similar to other display technologies [2]. Apart from not emitting light it also has the advantage that it is very low powered as it only requires power when changing a pixels state. However, to control an E-Ink display requires complex electronics circuitry to function and the displays are typically bought in predefined rectangular sizes making them difficult to integrate into arbitrarily sized or shaped prototypes or products, and they are rather expensive.

Compared to this, the technology used in this thesis - electrochromic materials - are non-light emitting and require only simple electronics. Electrochromic materials are materials that can change state from color to color or color to colorless (transparent) and be printed in any shape or form which means that they have the potential of avoiding some of the restrictions other display technologies have (see Fig. 1.1). Furthermore, they require relatively low power (1.5V) to change state and therefore do not necessarily require complex circuitry to control. However, in the past most research in these materials has been for Smart Windows and the fabrication of these displays has been restricted to those with expert knowledge and expensive equipment.

This thesis is part of the research project DecoChrom [1] which aims to move printed graphics from static prints to the interactive world using electrochromic displays. The project is funded by the European Union's research and innovation program Horizon 2020 under grant no. 760973. The DecoChrom project will develop mass producible ultra low-power and print industry compatible interactive graphics solutions for ambient intelligence. Thirteen interdisciplinary partners, balanced between researchers and industry where the chemical side will work on adding more electrochromic colors and mass producing electrochromic materials, and the design side on making interactive product prototypes with integrated electrochromic displays.

As with electronics and prototyping techniques, we need a democratization of display technologies that are not light emitting. Therefore, this thesis aims at providing fabrication tools for creatives with no expertise or knowledge of electrochromic technology. Furthermore, Eckert and Stacey highlighted the importance of existing application cases for design inspiration [5], therefore, due to the limited variety of application cases currently in existence, the thesis also aims at investigating innovative use cases for electrochromic displays. These examples can serve as design inspiration for designers, thereby helping with potential adoption of the technology and the democratization process.

Specifically the thesis aims at answering the following research questions:

1. **How can we create a toolkit for designers or creatives that eases the development of electrochromic displays?** In many areas electrochromic displays differ from standard printed graphics in that there are certain requirements for materials, substrates and their design. This in part has caused the technology to be limited to industry, experts and researchers with the required knowledge of how to design and construct such displays. By answering this question the possible outcome is the reach of the technology will be broadened and more industry and researchers will be aware of it.
2. **In which application scenarios are electrochromic displays a feasible technology?** With the ability to create a flexible display in any shape or form without the restrictions of previous display technology there are opportunities that were not previously available. Furthermore, because the technology is transparent and non-light-emitting it should be possibly to integrate it in scenarios previously not possible due to technological restrictions. This research question seeks to investigate those scenarios by creating prototypes utilizing electrochromic displays which also helps giving designers and developers inspiration of what is possible with the technology.

1.1 Thesis Structure and Scope

Fabricating an interactive electrochromic device encompasses three areas; materials, graphical design and fabrication. While Chapter 2 presents the reader with a brief

[1] https://cordis.europa.eu/project/id/760973

explanation on electrochromic materials and the chemical reaction, this thesis will not address those any further as the aim is on applying already well researched solutions.

Chapter 2 presents state-of-the-art work in personal fabrication, printed electronics and thin film displays after which a brief explanation of electrochromism and electrochromic devices is presented. Chapter 3 presents first an overview of the previously researched and used methods and techniques for coating or applying electrochromic material to a substrate and a description of why most of these methods are not friendly or usable to non-experts. Then the two toolkits developed are presented and finally unpublished research on inkjet printing electrochromic devices is presented. Chapter 4 presents the prototype applications developed during the DecoChrom project and in which areas these devices fit well. Chapter 5 presents the conclusion of the thesis and future work.

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Chapter 2

State of the Art

In this chapter we review the related work in areas that are relevant for this thesis. These include *Personal Fabrication*, *Printed Electronics* and *Thin Film Displays*. Furthermore, a general description of electrochromism and electrochromic devices is presented. The advancements in each of the fields have provided the background that allows to create personal fabrication techniques for electrochromic displays.

2.1 Personal Fabrication

Neil Gershenfeld coined the term personal fabrication in his book *"Fab: The Coming Revolution on Your Desktop – from personal computers to personal fabrication"* from 2005 in which he describes how he believes fabrication will have a similar trajectory as personal computers [15]. Where computers were once only available to a select few, and companies, they have since become a part of our everyday lives. Since 2005 the field of personal fabrication has indeed seen a similar trajectory with 3D printers, laser cutters and CNC mills becoming increasingly more available to consumers who are now able to produce artifacts in a variety of materials, sizes and qualities. All designed by users themselves or downloaded from a wide range of online services that provide free designs for each fabrication technology.

For a technology to become usable in personal fabrication, conditions in four categories (*Hardware and materials*, *Domain Knowledge*, *Visual feedback and interactivity*, *Machine specific knowledge*) must reach a certain level [7]. The *hardware and materials* which are typically expensive and industrialized must transition to a more consumer friendly price range and form. Industry professionals have a wealth of *domain knowledge* that enable them to create high-end products using their respective technology and while it is not necessary to provide all this knowledge to a non-expert, at minimum, tools that handle some of the knowledge should be provided, e.g. software toolkits. Additionally such tool should be able to provide the user with *visual feedback and interactivity* and remove or at least alleviate the need for the user to know *machine specific knowledge*.

Since 2010 research in personal fabrication has seen an increase across multiple fields such as architecture and robots, computer graphics, textiles, and human computer interaction (HCI). In the field of computer graphics research has been presented on providing systems that help the user detect whether a 3D design is structurally sound and also on varying the elasticity of the finished design even when being printed using a stiff filament [62, 64]. For those that use lasercutters, systems have been presented that alleviate the process of packing cut designs optimally to reduce wasted material, tools for fabricating sturdy objects and to automatically detecting which material is put in the lasercutter thereby alleviating the need to risk destroying parts of a material to find the right settings [8, 14, 63].

Architects mostly focus on large-scale fabrication, however, HCI researchers have explored how to fabricate large-scale sculptures using desktop 3D printers where bottles are used as beams and the joints are printed on a 3D desktop printer. The structure design software calculates all the engineering required enabling non-engineers to design structures using the system with follow up research enabling the user to design and fabricate large-scale kinetic structures [41, 42]. Designing architecture is traditionally done on either paper or using computer-aided design software but with advances in small-scale robotic arms and increased computing power of computers and graphics cards researchers have explored frameworks for human-robot interaction in the creative design process [29]. Even achieving continuous interactive changes to a work-piece using a robotic arm by a sensing glove worn by the user where a heat gun is mounted on the robotic arm and heats areas of the work-piece enabling live designing and shaping [47]..

In the field of textiles, there has also been an increase in research exploring personal fabrication in creating textiles. A low cost tabletop jacquard loom was presented in 2021 where components are fabricated using a desktop 3D printer and assembled on a frame consisting of the same aluminum extrusions as seen in the world of both commercial and do-it-yourself desktop 3D printers and lasercutters. The loom requires the user to manually weave between each row, however, the design for the overall pattern is created on the computer and then through a USB connection controls the loom row-by-row [3]. Other examples explore soft circuit prototyping using punch needling where instead of drawing electronic circuits on paper or a computer, conductive wire and wearable electronics prototyping components are used instead [16, 32], how to vary fabric volume and stiffness by changing yarn parameters and stitch patterns [2] or software tools that reduce the complexity of creating knitting patterns and enabling the creation of patterns from simple 2D designs or 3D models [22, 24, 35, 71].

In the broader field of HCI, exploration in personal fabrication has grown rapidly in later years as more technology become more easily available. This is evident in the rise of research that investigate lasercutters, CNC machines, 3D printers and electronics. For lasercutters the research use or improve on lasercutters ranging from realtime control of a lasercutter to systems that detect the material put in the machine and automatically set the optimal settings for the material to making press fit mechanisms in the lasercut material [1, 6, 10, 14, 21, 38, 58, 59, 68]. For CNC machines the research ranges from creating a pop up machine that can easily be fabricated to using a CNC machine for sketching [44, 52, 53]. In the space of 3D printers the research range from 3D printed fabric to using photochromic ink to recolor 3D printed objects [9, 42, 55, 56, 60, 66]. And for electronics the research ranges from creating inkjet circuits on soft substrates to embedding electronics into 3D printed objects [11, 13, 28, 31, 40, 72].

All of this research add to the breadth of personal fabrication in one way or another and while this is only a small amount of the research in HCI, it is outside the scope of this thesis to mention all the research that has been published on personal fabrication. However, this thesis adds to the field by introducing new methods for fabricating electrochromic displays using both low-cost off-the-shelf hardware as well as a custom designed system. Moving the fabrication of non-light emitting displays into the field of personal fabrication.

2.2 Printed Electronics

The field of printed electronics has in recent years seen a drastic increase of research. However, in this section the focus is specifically in the area of HCI and Ubiquitous Computing, where more and more works develop novel prototyping methods for printed electronics. As opposed to traditional electronics that are rigid and flat, printed circuits enable electronics on deformable and thin substrates which can integrate with other materials and cover large areas [65]. One of the first examples of this presented a variety of sensing application created using ink-jet to print conductive materials [17]. Later the Midas platform was presented which use vinyl cutting to fabricate custom touch sense circuits [61]. A method was proposed to use standard software and consumer inkjet printers to print circuits [37] which has since allowed the creation of a variety of applications such as deformation sensors [57], energy harvesting devices [33], touch sensors [18, 34, 49] and epidermal pressure sensors [23]. Furthermore, printing double-sided conductive ink enabled the creation of a electrical stimuli paper glove that provide tactile sensation [36]. Another approach, Foldio, utilized a range of fabrication methods and mechanisms to create actuation capabilities [50].

Apart from using inkjet printing, vinyl cutting and screen printing to fabricate printed electronics, hydro printing has also been presented [20]. Water transfer printing enable circuits to be printed on highly curved geometries that look organic. Furthermore, screen printing was considered as a DIY technique for embedding interactivity onto a wide range of substrates [43]. Through workshops in STEAM contexts (Science, Technology, Engineering, Arts, and Mathematics) they found that screen printing has a low barrier to entry and facilitated smart material fabrication in a collaborative environment and with creative engagement.

The fabrication techniques developed in this thesis builds on the previous methods by employing screen and ink-jet printing to create the displays. Furthermore, this enables combining printed electrochromic displays with other prototyping techniques thereby facilitating integration into a wider array of prototyping pipelines for printed electronic devices.

2.3 Thin Film Displays

In thin film display technology there are primarily two types of technologies, pixel based or graphically segmented displays. For pixel based the most current displays such as LCD, E-Ink and OLED technologies use numerous pixels to display graphics that are changeable. Whereas graphically segmented displays can only display the predefined shapes such as seen in numeric LCD displays. While the graphically segmented displays offer less dynamicity in that it can only present the predefined information, it can be fairly easily fabricated using various means, in a variety of forms and shapes. Thin film displays can be fabricated using a variety of materials such as electroluminescence [39, 51, 69], ultraviolet [25], thermochromism [45, 54] and electrochromism [5, 39, 48]. Each of these materials have advantages and disadvantages where for e.g. thermochromism requires exact temperature control which makes it hard to control, ultraviolet displays visibility is low in daylight conditions and therefore require additional light sources. Electroluminescent and electrochromic displays can be fabricated easily at low-cost, require low-power, are fobust and flexible. Fabricating electrolumiscent displays can be performed using different techniques such as ink-jet or screen printing the substrate layers [51] and cutting segments from electroluminescent films [4]. Different application cases have demonstrated the possibilities using a design space with different materials including integrating the displays with textiles [27, 51]. Later, the design space was through exploration extended to add pen interaction [39]. Electrochromic displays have promising properties, they do not emit light and stay stable for an amount of time without power, and have slow switching times between states, similar to E-ink displays. Previous work investigated manual fabricating processes [5], mass-manufacturing [12] and multi-layered color displays [19, 67]. So far, the main application case that has been researched for electrochromism is smart windows [19, 26, 67] where recently other applications in HCI has been explored. An 8-segmented EC display was presented in [39] and the opacity of an electrochromic display was used to indicate dust levels in a vacuum cleaner [39, 70].

This thesis extends the line of work by scaffolding the process of fabrication for non-experts while also exhibiting the capabilities of electrochromic display technology for HCI prototyping. Compared to previous work, detailed instructions on design, printing and fabrication of electrochromic displays are provided, enabling non-experts to create displays for both wearable and mobile human-computer interaction prototypes.

2.4 Electrochromism

The defining feature of electrochromic materials is the ability to reversibly change visible state when electrical current is applied. This change in state can be between colorless and color or be between two different colors. The change happens due to an electrochemical reaction (see Eq. 2.1) in certain metals and organic materials. Tungsten oxide (WO_3) is the most researched metal and used extensively in smart windows. [19]

$$WO_3 + x(M^+ - e^-) \rightleftharpoons M_x WO_3 \tag{2.1}$$

When a charge is applied, hydrogen ions (H^+) or lithium ions (Li^+) are injected, indicated by M in Eq. 2.1, the WO_3 changes to a colored state ($M_x WO_3$) and extracting them bleaches the WO_3 rendering it transparent and colorless. While tungsten oxide is one example there exists many materials that exhibit electrochromic properties when lithium or hydrogen ions are inserted or extracted [46].

Enabling the injection or extraction of ions is performed by an electrolyte that connects two separate layers or fields of material with one of them being either an ion storage layer or electrochromic layer and the other an electrochromic layer. The electrolyte facilitate the ionic movement between the two thereby allowing the electrochromic material to change state. The important part of the electrolyte is to be electronically insulating but conducting ions. Electrolyte can be made in gas, gel or solid form depending on the chemical materials used which enable a wide range of types of electrochromic devices such as smart windows, rearview mirrors for cars and bendable displays to mention a few.

2.4.1 Electrochromic Devices

To facilitate the connection between the electrochromic fields and the electrolyte there are a two layering techniques typically used to construct a device, namely vertical stacked and co-planar. However, they can also be combined. Vertical stack is the simplest method where the different materials are layered on top of each other (see Fig. 2.1, left) with the electrolyte in the middle of the construction. This is also the layering that has been exceedingly researched for use in smart windows where glass panes are coated with conducting and electrochromic material and when the panes are placed in the window frame the gap between them is filled with a gas form electrolyte. This method has the advantage that if the substrate where the electrochromic material can be printed on is pre-coated with a transparent conductor, making it possible to use both conducting and non-conducting electrochromic material can be used. However, because there are only two surfaces to print on, for interactive graphics this presents a limitation.

Co-planar designs (see Fig. 2.1, right) circumvent this limitation by having the electrochromic material next to each other and electrolyte on top making the connection horizontally. While this increases the range of possibilities for interactive designs, it can also substantially increase the complexity electronically. Where a vertical stacked device requires only two connections for power, a co-planar design require a connection for

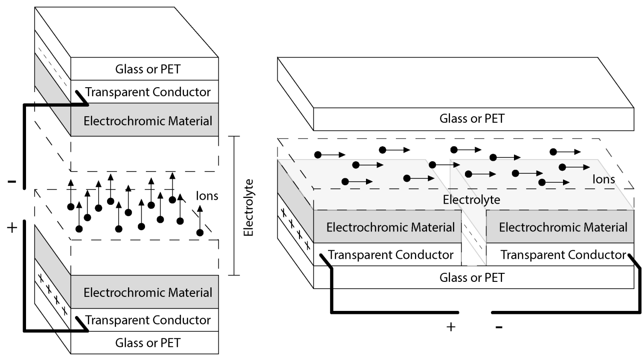

Fig. 2.1: General vertical stacked layer setup for electrochromic devices. [30]

each field of electrochromic material. In order to switch each of the fields individually those connections have to be able to be both positive and negative setting a requirement of the hardware that drives the device. Furthermore, with vertical stacked designs the substrate is typically pre-coated with a transparent conductor such as indium-tin-oxide (ITO) which makes it easy to print on, but for co-planar designs this is a limitation as the conductor will have to be broken between each field to avoid short circuits. Therefore, co-planar designs are most suited on substrates without a pre-coated conductor, however, this requires the electrochromic material to be conductive or an extra layer of printed conductive material.

2.5 Summary

Personal fabrication has gained a lot of interest with researchers as well as the maker scene, and we have already seen several technologies being democratised to these groups. For example 3D printing and electroluminiscent displays [51], that have gone from laboratories to makers or laser cutters becoming available at relatively low cost. Electrochromic displays are another suited technology for this, as they the base materials are comparably cheap, however, to facilitate this, the know-how needs to be available in a suited manner with acceptable design and printing tools.

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Chapter 3

Fabricating Electrochromic Displays

This chapter presents a brief overview of the currently used fabrication techniques for electrochromic displays and why most of these are not readily available to non-experts. The overview is concluded with a section on the challenges fabricating this type of display. The following sections presents the contributions of the thesis. Firstly, the toolkits developed and researched through the thesis employment period. Secondly, a section on research conducted on using ink-jet printing. And, finally, a summary of the contributions.

3.1 Overview of Fabrication Techniques

In 1969 the first article on electrochromism was published by S. K. Deb [13] and in 1984 it was proposed that electrochromic materials could be used in "Smart Windows" by Svenson and Granqvist [42]. In 1999 the first paper was published by James Coleman et al. on interdigitated electrodes (co-planar stack) in electrochromic displays [11] and in 2010 the first paper was published that used fabrics as the substrate by soaking spandex in electrochromic materials [20]. However, despite a yearly increase in researchers publishing in the field of electrochromics with nearly 8000 papers published on the subject in 2021 alone (see Fig.3.1), only very few are investigating ways to make the fabrication easier for non-experts. Much of the research is investigating how to improve the chemicals for better contrast ratio, faster switching times and adding more electrochromic colors. To this date many of the fabrication methods used in this research require expert knowledge and have been developed for very specific purposes.

The following is a list of currently used methods for applying electrochromic materials to a substrate:

- *Electrodeposition* use electricity to create metal oxide coatings on conductive substrates. For producing electrochromic coatings, typically three electrodes

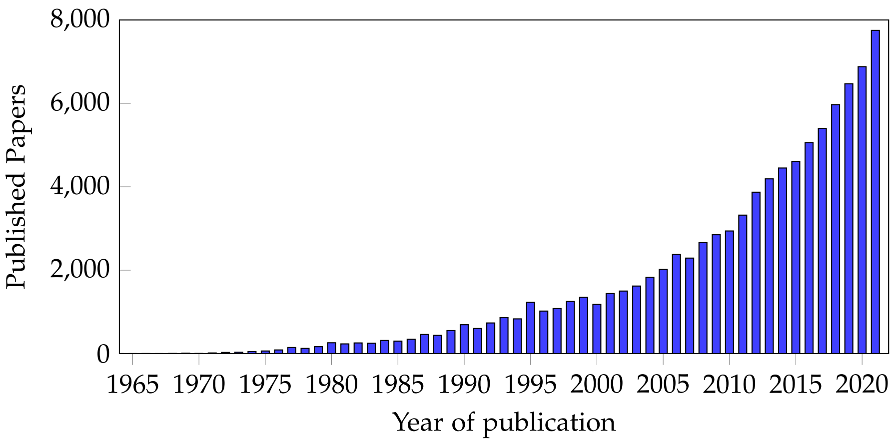

Fig. 3.1: Histogram of Google Scholar results per year using "electrochromic" as search word.

are submerged in an electrolytic liquid where the working electrode is either flourine-doped tin oxide (FTO) or indium tin oxide (ITO) glass or plastic. When electrical potential is applied to the three electrodes metal ions move to the working electrode thereby coating it. The method itself is relatively easy and fast, provides precise control of the thickness of the electrochromic layer and can be performed at room temperature. However, the preparation of the electrolytic solution and post processing the coated substrate requires up to 48 hours and annealing temperatures up to 500 °C. [36]

- *Sol-gel* is a two-step method where nano particles are suspended in a monomer solution forming a colloidal [1] suspension of nano particles (sol). Through hydrolysis [2] the solution creates a polymerization reaction creating an interconnected network (gel). Depositing the solution (sol) is performed using spin-coating, dipping or spraying. Because the sol step is a wet solution this method is particularly good at producing thin films, however, the drawbacks are shrinkage during drying, expensive raw materials, time consumption and annealing temperatures up to 560 °C. [1, 36, 46]
- *Spray pyrolysis* utilize heat to decompose salts to a target material. By spraying onto a heated surface the droplets go through decomposition thereby creating crystallite or clusters of crystallite. Following the thermal decomposition, the constituent elements recombine and through sintering crystallize the clusters of crystallite. This process continues till a film of the target material forms. It is a relatively cost-effective and simple method as it can be applied to a variety of materials such as ceramics, glass and metals. For several decades it has been used to produce high-quality and large-area films of uniform thickness in the glass industry. One advantage of the technique is that the heating can work in ranges of 100 °C - 500 °C. The disadvantages are uncontrollable droplet sizes

[1] A colloid solution is where insoluble particles are suspended in another substance.
[2] Hydrolysis is the reaction of a chemical with water, creating two or more new substances.

creating non-uniformity of the resulting films, low deposition rate and wastage of solution. [36]

- *Chemical Vapor Deposition* use gaseous reactants to produce high-purity composite materials, powders and bulk materials. The substrate to be coated is placed in a chamber after which, typically, volatile precursors [3] are circulated. By heating the substrate the precursors will decompose or react creating a thin film, and exhausting the chamber will remove unreacted precursors and by-products. One advantage of this method is the ability to produce films on shaped pieces, however, the disadvantages are that some of the precursors are explosive, corrosive or highly toxic. [36]
- *Thermal Vapor Deposition* use heat instead of precursor reactions to coat substrates. A solid material is heated to a temperature where it produces a vapor cloud in a chamber in vacuum and the substrate is then coated with the vapor. The advantages of this method is depositing low contaminated thin films and large source materials can be used per deposition run. The disadvantage of this method is that it requires costly and large RF power supplies. [36]
- *Sputtering* use DC current or RF (radio frequency) to eject ions or atoms from a source material onto a substrate. The source material and the substrate (typically silicon wafers, FTO or ITO-coated glass) are placed in a vacuum after which the source material is charged with either DC power or RF. If the source material is metal DC powering is used whereas non-metal sources use a high-frequency AC power source. The advantage of using sputtering is that it works with a wide variety of electrochromic metals, has good adhesion and reproducibility and does not necessarily require high temperatures. The disadvantage is that the sputtering system requires complex electronics, vapor chambers and gasses. [36]
- *Screen Printing* use a mesh to print a source material onto a substrate with a stencil on or in the mesh blocking out parts where no source material is to be printed [7]. The mesh is typically made up of very small nylon threads and stretched onto a wood, metal or aluminum frame. Thickness and quality of the printed material is adjusted by the amount of thread in the mesh with smaller number and thicker threads resulting in coarser and thicker prints and higher number and thinner threads resulting in finer and thinner prints. Stencils can be applied to the mesh using either emulsion based solutions that coat the inside of the mesh and are hardened with UV or tape on top of the mesh. Emulsion based stencils offer the best quality prints and provide a means for easily printing multiple prints with the same design. The advantages of this method are that disconnected details can be printed and thickness can be controlled. The disadvantages are that for high detail and emulsion based stencils it requires access to a wet area where the mesh frames can be washed with medium to high pressure water, the preparation of frames takes time for the emulsion to be coated, cured and dried, and it requires a dark room with a high powered UV lamp to properly cure the emulsion. While the fabrication method is mentioned in this overview, no previous work has published guides or toolkits on how to

[3] A precursor is a chemical compound that through reaction creates another compound.

use screen printing for fabricating electrochromic displays and only few mention using screen printing as a fabrication method [5, 9, 18].

Each of these methods with the exception of screen printing require heavily specialized hardware and in many cases in-depth knowledge of the chemicals and systems used. Some are directly toxic requiring not only specialized hardware but also proper safety gear and ventilation. While each of these methods have been developed for their specific purpose only screen printing has the potential to be used in a toolkit for non-experts as the hardware can bought relatively cheap and the knowledge required to screen print is minimal.

Apart from the fabrication method itself, there are also a few considerations that have to be taken into account in order to produce high quality electrochromic displays. Some of these are unique to the technology and therefore require the toolkit developed to address them either directly or indirectly. A high quality electrochromic device should have high contrast, meaning, high vibrancy of color when colored and high transparency when colorless, while at the same time be very stable. A display being stable can keeps its state for up to hours before needing another charge. In the following section these considerations will be described.

3.1.1 Design and Fabrication Considerations

Electrical conductor: Electrochromic devices have in the past used glass or polyethylene terephthalate (PET) plastic coated with indium-tin-oxide (ITO) with the latter functioning as the transparent conductor. For vertical stack devices this is ideal as printing can happen directly on the ITO side of the substrate. For transparent flexible displays, PET-ITO is also a good combination as devices fabricated using this can be bent to a radius of 0.7cm before the ITO begins to crack and the electrical connections in the device start to deteriorate. Also, because it is already conductive both non-conductive and conductive materials can be used and it simplifies both the design and fabrication. However, for co-planar devices a pre-coated substrate requires an additional step breaking up the ITO into separate fields where the electrochromic material is to be printed. Therefore, co-planar devices with their increased ability to be fabricated with more complex electrochromic designs is best fabricated using non-conductive substrates. This opens up the possibilities of which substrates these can be printed on e.g. paper and fabric. It does, however, require using either only conductive electrochromic material or adding another step to the fabrication where conductive material such as silver is printed. Having to print the electrical leads along with the electrochromic material increases the complexity in both the design and fabrication phase.

Thickness of electrochromic material and electrolyte: Each of the fabrication methods listed previously has one thing in common in that their purpose is to precisely and uniformly coat substrates with electrochromic material at specific thicknesses. The thickness is very important to the contrast ratio as a too thin layer reduces how colorful a display can be but at the same time a too thick layer reduces how transparent it can become. Finding the right thickness is therefore important for optimal contrast ratio and any fabrication method has to be able to adjust the thickness. In a vertical stack device it is most important to avoid a too thin layer as the two conductors has a chance to connect and short circuit the device.

Electrical resistance: Depending on the materials used the electrical resistances can affect a device greatly. For devices using PET-ITO this can mostly be ignored as the ITO typically has low resistances (50-250Ω/sq), however, for larger devices (>10x10cm) adding a conductive trace using silver or copper along the edge of the device can improve performance but will require additional steps during fabrication. For co-planar devices where using PET-ITO is not advantageous one option is to only use conductive electrochromic material. However, because the thickness of the electrochromic material must be controlled for optimal contrast the resistances can be affected greatly lowering the potential sizes of the displays. A better option is to instead print specific electrical traces using conductive material such as copper or silver.

Design considerations: Because an electrochromic device consists of multiple materials that are put together during the fabrication process the design must include these. For vertical stack devices this includes a small margin and a border around the printed graphics. The margin ensures that the spacing material keeping the bottom and top substrate together is not too close to the electrochromic parts of the print (see Fig. 3.2). In case this happens the electrolyte will not be able to properly cover the electrochromic material and there will not be any change where this happens. As ITO is fragile it is best to add an area outside of the border where stronger and less fragile material can be added such as copper tape. When considering a design for an electrochromic device these additions increase the overall size of the display, e.g. if the graphics are designed to be 5x3cm in size then the additional border and margin will add approximately 5-6mm on all sides. For co-planar devices the same applies in addition to also requiring designs for conductive traces if the electrochromic material itself does not provide sufficient conductivity. Furthermore, if a device is non-uniformly shaped it can add difficulty applying the spacer material due to the curves and shapes of it whereas for rectangular devices the spacer material can be cut to strips and applied along each border making it easier to fabricate a square device versus a non-uniformly shaped one.

Material curing: As the inks and electrolyte initially are in either liquid, paste or gel form, they have to be cured to remove unneeded parts such as e.g. water or solvents. Curing typically happens using either heat or UV light depending on what the ink or electrolyte is composed of. For example, the electrochromic material PEDOT:PSS from Sigma Aldritch mostly consists of water (H^2O) for both the ink-jettable mix as well as the screen-printable paste which means to cure this material requires up to 100-110°C of heat. Whereas the electrolyte provided by Ynvisible [4] contain a UV hardener which requires UV light to cure. Both of these inks require extra hardware to cure, a heat source for the electrochromic inks and a UV lamp for the electrolyte. Some conductive inks also require heat while others only require specific substrates, e.g. resin coated substrates where the solvent in the conductive ink soaks into the resin with the conductive parts staying exposed. Because the electrochromic ink requires up to 110°C of heat to cure, there is a slight disadvantage in that any substrate has to be able to be heated to that temperature without presenting wobbling, warping or melting.

In the following section are the contributions to fabrication methods. Each method

[4] `https://www.ynvisible.com/`

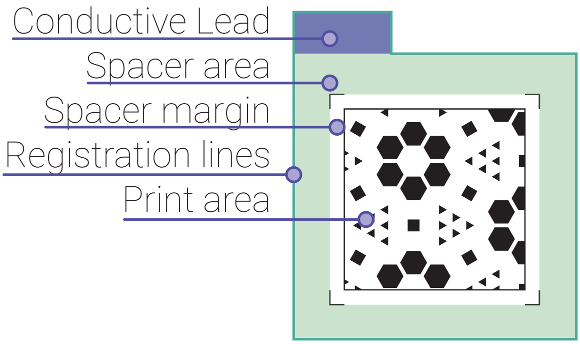

Fig. 3.2: Design parts for a vertical stack design including print area, registration lines, margin, spacer border and additional strengthening area for conductive leads. (Part II, Paper A) [22]

approaches the way of fabrication differently and with varying degrees of manual labour; ranging from each step is performed manually to nearly fully automated. Despite this, each method attempts to address the considerations either by informing the user of how to best approach fabricating an electrochromic device or by using optimal settings in software (ink and electrolyte amount and curing time) and then print using those settings.

3.2 Contributions

3.2.1 Screen Printing

To enable a low barrier of entry, the first toolkit developed (presented in Part II, as Paper A) use screen print (see Fig.3.3) and ink-jet technology [22]. This was chosen as commercial screen-printing kits containing all the required hardware and materials are inexpensive, readily available, does not require expert knowledge to use and is a well-known method. One advantage of this method is that the thread count of the frame allows to control print detail and amount of deposition This is ideal for electrochromic devices which require very precise thicknesses of material. It typically takes a day from design to finished device as frame preparations take time to coat and dry. Besides the scientific publication [22] detailed step-by-step instructions were made available in a wiki [5]. Here we also provide best practices to produce good quality prototype devices. Furthermore it also provides instructions on how to make ink-jet printers Canon Pixma IP110 and Brother MFC-J480DW work with electrochromic inks. While ink-jet printing provides faster turn around from design to fabrication the finished devices typically lack in quality. The non-conductive Prussian Blue electrochromic material can be printed in one print but provide slower transition speeds and overall lower switch counts before degradation and the conductive PEDOT:PSS requires three prints to build up enough electrochromic material and each time the substrate is removed and

[5] `https://github.com/DecoChrom/Wiki/wiki`

Fig. 3.3: *Left:* Frame with negative stencil. *Right:* Squeegee being moved across the frame pressing ink through the exposed parts. (Part II, Paper A) [22]

re-inserted into the printer imprecision's occur making for a lower quality device.

Throughout the research project this toolkit has been extensively used to fabricate in excess of over 600 displays. With half of the displays being fabricated as part of the workshops that have been conducted over the world and at premiere conferences [27–29, 33]. Furthermore, the application cases contributed and presented in the next chapter have all been fabricated using this toolkit.

3.2.2 Syringe Depositing Printing

The second toolkit developed (presented in Part II, as Paper B) use syringes to deposit the required material for an electrochromic display. Using a 2D Plotter frame as a base for the printer, tool changing was developed to enable printing all the materials without the need for user intervention during printing. Where screen-printing or ink-jet printing require the substrate with newly printed material to be heat cured in e.g. an oven, this toolkit had tools developed that provide both heat curing and UV curing so after each material is deposited it can be cured before the next layer is printed. The printer has five tools; three tools with syringe depositing capabilities for printing the conductive, electrochromic and electrolyte material, one tool for heat curing the conductive and electrochromic material, and one tool for UV curing the electrolyte. The depositing tool use a finely linear actuator to push or pull the syringe allowing for precision control of the volume of the ink being deposited. Standard 1mL syringes are used with exchangeable tips which provide the ability to adjust the width of the deposited material where e.g. less viscous materials require larger tip to reduce the required pressure to press out the material and viscous materials can use thinner tips. Printing both the conductive and the electrochromic without the need for a conductive substrate enables the printing of co-planar devices, which increases the possible complexity of the displays. A display printed with this toolkit take 30 minutes to 2 hours to print, heavily reducing the time it takes to iterate and prototype electrochromic displays. The biggest limitation is the 1mL syringes which restricts the maximum size a display can have where especially the electrolyte is limiting the size due to the amount of material is required versus the electrochromic and conductive.

3.2.3 Ink-jet Printing Research

For many years ink-jet printing has provided very fast iteration times for graphical designs. In recent decades even printed electronics has reached a level where consumer printers can print electronic circuits to quickly iterate electronic designs. Examples have been shown where full circuits have been ink-jet printed on stretchable substrates, tattoo and transfer paper, and shrink film using off-the-shelf inks for the conductive traces and using a consumer printer [4, 19, 24, 26, 39]. These examples also include printing PEDOT:PSS, however, as a transparent conductor and not an electrochromic material. An attempt to build on this research and make a toolkit based on ink-jet printing was conducted.

Previous research presented work where silver ink and PEDOT:PSS was used to print circuits. If the resistance of the conductive layer was too high multiple prints could alleviate this by reprinting the same pattern to build up either silver particles or PEDOT:PSS. We found that printing PEDOT:PSS using consumer printers required at minimum three prints to build up enough material for visual contrast and reduced resistance. This process requires the user to re-enter the substrate for each layer which has a very high chance of causing minor misalignment's between each print. For simple prints this might not pose a problem, however, for designs that are complex, precise and fully utilize the ink-jet's printing capabilities they will pose a problem. To alleviate these factors and create a system where conductive and electrochromic materials could be printed with minimal imprecision and without user intervention the idea was to provide a solution where this re-entering of the substrate would not be needed e.g. by increasing the amount of ink being deposited during printing. Furthermore, if using an ink-jet printer with more than six cartridges, a fully integrated printer could be realised where two cartridges would be used for conductive and electrochromic and the others for black, and the standard color cartridges. This would mean that the electrochromic and conductive parts could be fully integrated with a standard ink-jet print.

Printer drivers

To print a document the computer goes though a process of converting the document to be printed into a language that is compatible with the printer. Each printer has its own unique set of commands that controls the movement of the paper and the printhead in addition to droplet control. The ink droplets that are ejected from the printhead nozzle can, depending on the printer have two to three sizes, small, medium and larger with the smallest size used in high quality printing and large droplets in fast printing. Normally inkjet printers print row by row where each rows height is determined by the amount of nozzles on the printhead. Fast or draft printing typically print a full row at a time where high quality printing prints a full row at a time but moves the paper a quarter of a row at a time and thereby overlaying each row 4 times. Printing a full row without moving the paper is not a normal feature in the printer drivers which is why most research has used the process of re-entering the substrate into the printer and print the same design again to build up layers. To circumvent this and print all the required layers to reduce resistivity of the conductive inks and improve the contrast of the electrochromic inks a custom printer driver was developed

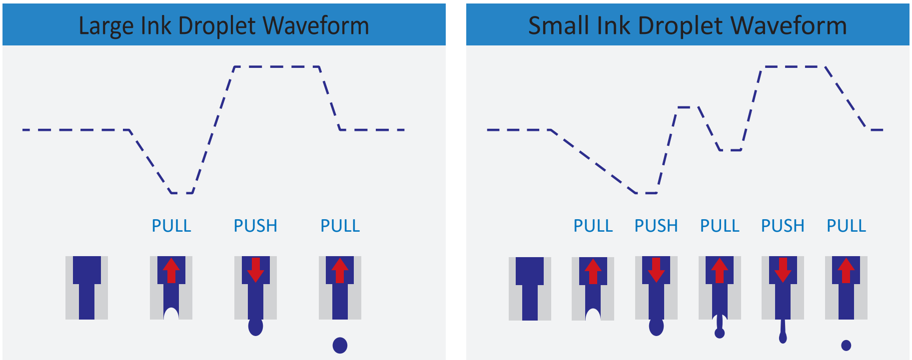

Fig. 3.4: Epson print head technology: Electrical waveforms control the motion of the meniscus in a piezo nozzle and can through this waveform control the droplet size.

for the Epson printers. Epson has a programming language (ESP/P) specific for their printers which allows more or less full control of how the printers behaves during printing. [6] The custom driver can read a jpg or png file and convert it into a txt file with specific instructions for the printer. Through this it is possible to precisely control both position and droplets of the resulting print, including printing the same row multiple times without continuing to the next row of the print.

Ink-jet Technology

Ink-jet printing use a drop-on-demand (DOD) method to deposit precise quantities of ink onto a substrate. The print heads responsible for the depositing of inks are typically using either piezo or thermal technology to deposit the droplets of ink. *Piezo printheads* use a meniscus at the tip of the nozzle controlled by a piezoelectric element to eject ink from the nozzle [47]. Ejected ink volume can be varied by precisely controlling the electric waveform (see Fig. 3.4) and the mist caused by residual vibration is controlled by rapidly suppressing the meniscus and thereby creating near perfect sphere droplets and straight ejections. *Thermal printheads* use a heat element to rapidly heat ink inside a small chamber in the printhead [3]. The ink is vaporised which forms a bubble of gas that force a drop of ink out of the nozzle. The heating element is switched off so the gas bubble cools, contracts and condenses. Multiple printers, print head technologies and brands were tested.

The following printers were tested:

- *Printers (Piezo printhead)*: Epson EcoTank ET-2650 [39], Epson ET-2720, Epson Stylus C88+ [16, 17, 32], Epson Workforce WF2010W [4, 10]
- *Printers (Thermal printhead)*: Canon IP100 (IP110) [24, 34, 35, 40, 45]

The printers were selected based on a variety of factors. Mostly due to previous research having used them but also the ability to easily swap inks with non-OEM

[6] https://reference.epson-biz.com/modules/ref_escpos/index.php?content_id=2

inks. E.g. the Ecotank printers from Epson were specifically designed to be used with non-OEM inks in that they have a refillable tank for each color build into the printer itself, whereas 3rd party refillable cartridges can be bought for the Stylus and Workforce brands. Those tanks and refillable cartridges can then be filled with whichever ink is to be tested. For the Canon printer the process is slightly different as no 3rd party cartridges were available, so the OEM cartridges themselves had to be modified which consisted of cutting off the top of the cartridge, cleaning the cartridge and sponge inside the cartridge, and taping it back together after drying. It could then be refilled from the bottom with the new ink. This process in itself is rather easy, however, taping it back together has to be done properly otherwise the new ink will spill over if there are any gaps in the taping.

Ink selection

Today's consumer printers can print very detailed prints due to their small nozzle sizes (20-30micron in diameter) [2] and this makes for high quality photo and document prints but presents a few challenges for using ink-jet printing with non standard inks. Viscosity, surface tension and particle size of inks has to fit within a very narrow space in order to produce proper droplet formation. We can predict a liquids printability, Fromm number (Z) [2, 21, 26], by evaluating its fluid dynamics, Reynolds number (Re), in relation to the dimensions of the printing nozzle, Weber number (We) (see Eq.3.1). The Reynolds number and Weber number's relation is the dimensionless Ohnesorge (Oh) number where the Fromm number is the inverse.

$$Z = \frac{Re}{(We)^{\frac{1}{2}}} = \frac{(dp\gamma)^{\frac{1}{2}}}{\eta} = Oh^{-1} \begin{cases} d = & \text{nozzle diameter} \\ p = & \text{density} \\ \gamma = & \text{surface tension} \\ \eta = & \text{viscosity} \end{cases} \qquad \text{(Eq. 3.1)}$$

Fromm reported that if a liquid has a Z-number lower than 2 then there will be printability limitations [15], whereas it was later proposed that DOD printing can work with Z-numbers between 1 and 10 [37]. If the Z-number is outside the range it will either create splashes or satellites, have too low energy or be too viscous. Another factor to take into account is particle size of the nano particle inks; the particles should be approximately 50 times smaller than the diameter of the nozzle to prevent clogging.

The following inks were used during the research and the corresponding Z-numbers calculated from datasheets where available:

- *Silver nano particle inks*: NBSIJ-MU01 from Mitsubishi Paper Mills (Z-number 9.52) [6, 23, 24, 31], JS-B25P and JS-A191 from NovaCentrix (Z-number 6.84) [12, 14, 16] and Sicrys^{TM} I40DM-106 from PVNanoCell (Z-number 2.88) [25, 43, 44]
- *Electrochromic inks*: Ink-jettable PEDOT:PSS from SigmaAldritch (Z-number 2.42) [26, 38, 41], PEDOT-JET40 from Ebay (Z-number unknown), and Prussian Blue from Frauhenhofer ISC (Z-number 9.25) [8, 22].

Each ink used has it's own particularity, curing temperature, substrate requirements and particle size which needs to be taken into account.

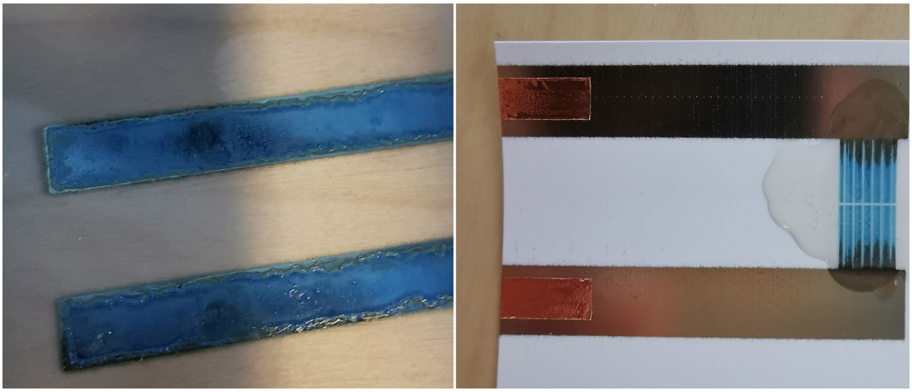

Fig. 3.5: *Left*: PVNanoCell development ink made specifically to be printed on PET and glass left residue on top of the silver making it unusable. *Right*: Silver ink printed on photo paper without problems, however PEDOT:PSS (blue) printed with clogged nozzles.

The NBSIJ-MU01 silver ink is specifically made to work with Mitsubishi's own resin coated paper and to cure at room temperature, meaning there is no need for it to be cured in an oven after printing. However, if the conductivity is not high enough, it is possible to slightly improve it by heat curing it for 3minutes at 80°-100°C. The ink prints consistently on both piezo and thermal printheads. Although it is specifically formulated to work with Mitsubishi's own paper, it still works with normal photo paper from e.g. HP or Kodak. In the fabrication method, Transprint (Section 3.2.1), Prussian Blue electrochromic ink was successfully printed with a Canon IP110 (thermal printhead) printer which means that this could be a possible solution for printing both conductive and electrochromic in one printer. However, as Prussian Blue is a non conductive electrochromic ink and PEDOT:PSS does not consistently print on the Canon IP110 printer, this combination does not work. Unfortunately, the NBSIJ-MU01 ink requires photo paper as a substrate in order to function properly. When printing on substrates other than photo paper the solvent used in the ink leaves a film on top of the silver particles which insulates it and renders it difficult to make electrical connections with other inks or electronics components as was experienced when printing on Epson Workforce WF2010W with PEDOT:PSS ink and NBSIJ-MU01.

The JS-B25P ink from Novacentrix also requires special paper from its manufacturer or photo paper, and this ink is specifically developed for and tested by the manufacturer using a Epson Stylus Color 88+. However, after following the ink handling procedure provided with the ink, it would never print using all the nozzles on the Stylus's we tested with, and after few tries it would completely clog the print head. This was attempted on multiple Epson Stylus Color 88+ as well as both the Epson EcoTank ET-2650 and Workforce WF2010W. Each batch of ink produced by Novacentrix is tested before being shipped and viscosity and particle size is of particular importance, and all received and tested batches of the ink were well within the acceptable parameters. Regardless of that, it was not possible to make this ink fully printable. Another ink, JS-A191, from Novacentrix that does not require a specific paper to be printable and can be printed on a wider array of substrates was tested. As opposed to room temperature curing it requires heat curing from 100°-140°C, which is similar temperatures as PEDOT:PSS requires, making this combination theoretically viable. However, as with the previous ink from Novacentrix, the nozzles would clog after a few prints. A cleaning ink was created based on the recipe provided in [26] which is supposed to help prevent clogging, however, once the nozzles were clogged they were completely unusable again. Furthermore, the JS-A191 would after printing on PET and heat curing, similarly to Mitsubishi NBSIJ-MU01 ink, leave a residue on top of the silver which is believed to be from the solvents in the ink which would insulate the conductivity (see Fig. 3.5, left).

The Sycris I40DM-106 from PVNanoCell was developed as an ink-jettable conductive ink to be printed on a wide array of substrates and has been specifically tested on PET and glass by the manufacturer using piezo printheads. Sintering the ink requires low temperatures (130°-150°C) but our experiences are that 100°-110°C also works, however, the conductivity will be lower. When printing on PET sheets with thicknesses similar to photo paper temperatures higher than 100°C will start to melt and warp the sheet, so lower temperatures are better for this type of substrate. This ink can successfully print on both of the two Epson EcoTank printers as well as the Workforce WF2010W (see Fig. 3.6, top), whereas on the Canon IP110 printing without any clogged nozzle was unsuccessful. While this ink has most successfully printed on the Epson printers, it still caused clogged nozzles after few (5-10) prints and without any means to clean out the print head (see Fig. 3.6, bottom). Cleaning the printheads have been attempted using the same solution as with the JS-B25P ink as well as in an ultrasonic cleaner but without success.

The PEDOT:PSS solutions from Sigma Aldritch come with varying concentrations of PEDOT:PSS in water (H^2O) ranging from 0.8% up to 5% and is being sold as a conductive solution and in some cases as a transparent conductor. The ink-jet version of their product line contains 1-5% ethanol and 5-10% diethylene glycol to make it ink-jettable with both of them altering the surface tension of the ink and the diethylene glycol improving evaporation rates and wettability [30]. Both of these additives are used to adjust the Z-number to be within a printable range. However, despite this, there were still problems with clogged nozzles. Printing would happen without clogged nozzles if continuously printing after refilling a cartridge and not letting the printer rest for more than approximately 30 minutes, if left for more than that without running a cleaning cycle with a cartridge of cleaning solution, they would slowly start to clog (see Fig.3.5, right). All of the Epson printer except the Stylus Color C88+ and the Canon Pixma IP110 were able to print this ink within those 30 minutes. To ensure proper contrast ratio between coloration and transparency three layers had to be printed, if less layers were printed it would not be vibrant enough while anything more than three layers and it would not become transparent enough. At the same, adding more layers reduced the resistance which increased its usability as a conductive electrochromic material. However, despite this, printing on photo paper heavily increased the resistance, mostly due to the resin coating on top of the photo layer, whereas printing on PET or glass, printing three layers without heat curing in between had a high chance of causing coffee stain build up of the PEDOT:PSS. Similar experiences were found with the other two electrochromic inks where the

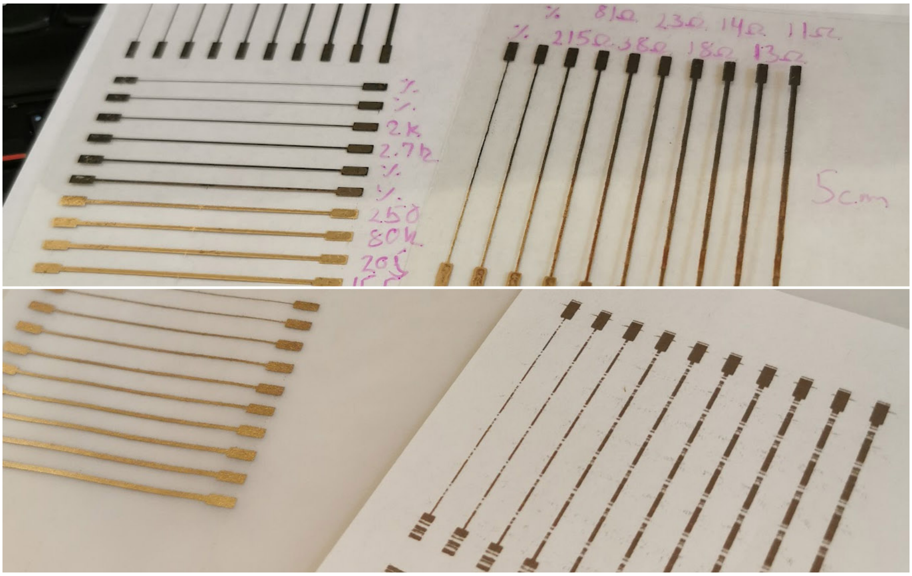

Fig. 3.6: *Top*: Sycris I40DM-106 ink test using 5cm lines with varying line widths printed both vertically and horizontally on PET and using Epson Workforce WF2010W with custom print driver, and heat cured at 100°C for 30minutes. *Bottom*: Clogged nozzles after a few prints.

PEDOT-JET40 had a heavily decreased resistance, to the point where five or more layers where required to build up a similar conductivity as the PEDOT:PSS solution. However, the PEDOT-JET40 had less occurances of clogged nozzles and unfortunately a datasheet was not available so information on the additives were not available and the seller did not reply to mails. The Prussian Blue consistently printed using the Canon Pixma IP110 but due to it not being conductive in itself, it was discarded as a usable solution in the overall plan for the ink-jet research.

Possible reasons for failure

Despite all the efforts put into making ink-jet printing work, even in different environments, in office at MIT (Boston, USA), in office at Aalborg University (Aalborg, Denmark and Hobro, Denmark), and at home (Aalborg, Denmark) it was not possible to make the printing work correctly, even though datasheets reported it should be possible and the calculated Z-numbers are within usable ranges. Potential reasons for this could be differences in temperatures between the different environments or humidity, the inks, while being tested from the manufacturer, could be of a different quality than the ones used in previous research, clumping of the nano particles, although each refilling of the cartridges used syringe filters to avoid this, the printers themselves are not up to the same quality standards in the different regions of the world. However, we can also not expect that for example makers or designers have the same office conditions as others which means that this is not a practical solution if the goal is to get this technology into as many hands as possible. So therefore it was decided to take a step back and develop a printer (Section 3.2.2) that is less affected by differences in the environment and is not as affected by the particularities of the inks.

3.3 Summary

This chapter presented the previously used methods for fabricating electrochromic displays and why these are not ideal for non-experts. To allow developers and designers gain access to the display technology in a way that enable quick prototyping and iteration two toolkits are contributed in Section 3.2.1 (Part II, Paper A) and 3.2.2 (Part II, Paper B) [22]. Both of these methods provide required hardware, instructions or software that facilitate the creation of electrochromic displays without the need for expensive equipment or expert knowledge. With these methods those who are interested can with relative ease prototype electrochromic displays providing the first step towards democratizing the technology. Furthermore, the chapter also presents research conducted on further developing a method that utilize only ink-jet printing.

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Chapter 4

Application Scenarios

While electrochromic display technology has existed for more than four decades the amount of variety in scenarios where it is used is negligible with smart windows and smart mirrors being the primary driver [7]. And the few presentations of other examples have only been in lab environments [2, 8, 16]. However, with the ability to easily fabricate and prototype displays that are flexible and transparent, more cases have been and can be explored. The toolkits contributed in Chapter 3 to easily fabricate electrochromic displays are only one part of democratizing the technology. If there are no examples showing the capabilities of what a technology can do, there will be minimal inspiration for those who do not yet know the technology. Therefore, examples presents an opportunity to showcase and inspire how electrochromic displays can be used for people new to the technology which is another important factor in democratizing the technology [4]. This chapter presents the contributed application scenarios.

4.1 Interactive Prototypes

Due to the low-power nature of electrochromic displays and the simplicity of powering displays they lend themselves to be integrated in relatively simple interactive systems [3, 5]. Powering a display can be as simple as connecting a small DC motor or solar cell [17]. Furthermore, because the displays themselves have capacitance they can be used as a touch sensitive devices [10].

An example of this is contributed in TransPrint (Part II, Paper A) as a transparent touch sensitive button example, where the displays functions as multimedia buttons that change when touched [10]. Furthermore, in Part III, Paper D and E the displays are controlled by a low-cost prototyping board (ESP32) [13, 14]. The ESP32 provides WiFi capabilities, such as the ability to connect to WiFi and create its own access point with a small hosted website. This website can be programmed to control the pins on the board which allows the displays to be controlled by WiFi enabled device with browsing capabilities such as smart phones, tablets and computers. A continuation of Paper D and E was implemented where instead of connecting through WiFi and using a web interface, a physical four button interface was 3D printed with electronics powered through battery connects to the lamp through Bluetooth. Each button on the interface would switch an individual display on the lamp. This prototype implementation has, however, not been published. Another example of this is contributed in Hybrid Settlers (Part III, Paper G) where fields on a board game are changed from the normal static pieces to interactive elements in the game [15]. Hexagonal electrochromic displays were created that fit the size of the normal static fields from the game, but contained two resources instead of one which could be switched during game play. The displays are controlled by an external controller that is used to add more dynamicity during a game by altering the resources. All of the contributed examples have been fabricated using the TransPrint method and the electronics and programming were implemented using either an Arduino or ESP32 prototype board showing that relatively complex interactive prototypes can be created using prototyping boards for novices.

4.1.1 Art and Decor

While the displays fabricated for the prototypes contributed are relatively small (maximum size of fabricated display is equal to an A4 paper), our partners on the DecoChrom project have made displays as large as 30x60cm (see Fig. 4.1). This shows that it is possible to make large scale displays that can be used for e.g. wallpapers where a walls appearance can be changed either rapidly or over time which enable creating interactive decor or art that can affect the look and feel of an environment.

Fig. 4.1: Example of wallpaper type electrochromic display. Fabricated by Ynvisible (DecoChrom partner).

One contribution (Part III, Paper D) utilize the transparency of electrochromic displays combined with high luminance LEDs to cast shadows and circumvent the size limitations of the electrochromic technology [14]. If the lamp is used as the only light source in a dark room the shadows will change the rooms environment. In the example contributed the shadows are linked to a book, so the effect of changing the feel of the environment is minimal, however, the shape of the lamp and the graphics on the displays can be changed to resemble those of traditional static shadow lamps.

In one of the examples contributed in (Part II, Paper A), the overlaying of electrochromic displays on top of traditionally static ink-jet printed graphics is used to create interactive art, where parts of the art piece have been modified to utilize the electrochromic displays ability to change between two or more pieces of printed graphics [10]. While this example only change between two parts of the art piece, it is possible to create a display with more. Also, the example is portrait sized but this

Fig. 4.2: Electrochromic Art Piece example of Banksy's *Girl with Balloon*. The girl is created with electrochromic display technology whereas the background and the balloon is printed using traditional ink-jet printing. The electrochromic display is overlayed the traditional print allowing the girl to appear as one with the background and disappear instead of being shredded.

could be designed to have the same size as seen in Fig 4.1 and by altering the power provided to the display it can be made to be a slow changing art piece.

The ability to fabricate transparent non-light emitting displays and use them in combination with traditional prints allow for a wide variety of creative possibilities for both art and decor. While size has the potential of becoming a technical difficulty, this can be avoided by making smaller displays and using them as pieces of a bigger displays.

Due to the ability to fabricate displays on transparent substrates with relatively high general visual transmittance they are ideal to be used in scenarios where graphics are needed as part of the display. e.g. background art with an interactive overlay. This enables a variety of uses in areas such as information systems and, card or board games. Examples of this are contributed in TransPrint (Part II, Paper A) as an interactive map where a walking route is super imposed on a forest area map and the user can then via buttons select which route is visible on the map or as an interactive art piece [10]. Another example of this is an electrochromic art piece that was made as an alternative to Banksy's shredding of his art piece "*Girl with Balloon*" during the auctioning of the art piece [1]. The ability to make the electrochromic graphics transparent were used to hide the girl into the background instead of shredding (see Fig. 4.2).

4.1.2 Wearables

Adding interactive display capabilities to fabrics has been attempted for many years with early examples using simple LEDs sewn into the fabric, to later being regular displays being stitched into a patch of textile [20]. While each of these methods do provide display capabilities to textiles, they do so by providing a clear rectangular surface where the display capability is and for the non-light emitting technology E-ink, the background is mostly always white providing a drastic contrast between fabric and display [18]. With electrochromic displays capabilities it will be possible to add display capabilities that seem more embedded and part of the fabric by leveraging the ability to fabricate displays in any shape or form and also their flexibility. Examples of this are shown in [6, 9] where display and fabric is patched together or in [19] where a display is fabricated to fit the form of the front of a shoe. However, this application is similar to previous examples of regular displays being stitched onto fabric.

VitaBoot (presented in Part III, Paper F) is a contribution to smart fabrics that approach adding display capabilities slightly different from previous methods [11]. Leveraging both the flexibility and ability to fabricate displays in custom shapes a shoe is developed and implemented where the sides of the shoe have an electrochromic display embedded as part of the shoe material. This example shows the benefits of the display technology and also present a novel approach to adding display to textiles.

4.2 Teaching

As the world becomes more technologically advanced due to new technologies being researched and developed, more workforce and education is required in the STEAM (Science, Technology, Engineering, Arts, and Mathematics) fields. For many years Makerspaces have been one area where some of these new technologies have been introduced such as 3D printers, lasercutters, vinyl cutters and electronics. Makerspace environments lend themselves to learning by doing where users, for the most part, have free access to the tools and necessary software with a supervisor available if any questions arise. Due to the manual approach required to fabricate electrochromic displays using the TransPrint method, Makerspaces present an ideal environment to introduce the technology. In Part III, Paper C the results and findings of running a week long workshop are presented [12]. To prove how easily it is for new comers to use the TransPrint toolkit developed in Chapter 3, the method was introduced the first day of the workshop with examples of what the technology could be used for. The participants were then required to create an artifact elucidating the stories of the female Atari developers that are mostly forgotten. Each artifact was required to include interactivity using electrochromic displays. Despite multiple groups of participants with no knowledge of any of the tools in the Makerspace, electronics or programming, all groups managed to fabricate artifacts that use electrochromic displays interactively. This indicates that the technology could work as an additional technology in Makerspaces for those who require non-light emitting displays in their prototypes.

4.3 Summary

This chapter presented prototypes that widen the span of examples of how electrochromic displays can be used. Where previously the range was small (smart windows and mirrors, and a few laboratory examples) the contributions presented shows how the technology can be used in wearables (Part III, Paper F), art and decor (Part III, Paper D), teaching (Part III, Paper C) and for interactive prototypes (Part III, Paper E and G) [11–15]. With each of these contributions the horizon of application scenarios has been broadened to the point where those unfamiliar with the technology should have enough variety to be inspired. While the toolkits contributed in Chapter 3 are one step towards democratizing the technology, the works contributed in this chapter adds another step towards it by showing how it can be used.

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Chapter 5

Conclusion & Future Work

In the pursuit of creating smart materials that blend into everyday life, many technological advances have happened in the fields of human computer interaction and personal fabrication where in recent years examples of printed electronics has moved from expensive to consumer level of hardware, 3D printing and electronics prototyping boards have also become readily available at inexpensive prices. However, for custom shaped non-light emitting displays there has been minimal progress. To address this, two research questions were asked:

R1. **How can we create a toolkit for designers or creatives that eases the development of electrochromic displays?**

R2. **In which application scenarios are electrochromic displays a feasible technology?**

To answer R1, two toolkits that allow to print electrochromic displays are contributed and one further approach was investigated. The contributed fabrication method TransPrint consists of a silkscreen kit, electrochromic and electrolyte inks, online best practice guides and the option to use ink-jet printing with all the materials for the method being readily available and inexpensive. This lowers the barrier of entry to fabricating electrochromic displays and enable those who are interested a relatively easy entry, nudging the technology towards becoming democratized. The method has been extensively used both in-house, by EU project partners and at various fabrication workshops held during the thesis period. Additionally, all of the electrochromic displays used in the application scenarios presented in Part III have been fabricated using TransPrint.

The second method contributed, ECPlotter, utilize syringe depositing in a custom designed printer that prints a display with minimal human-intervention and allow easy printing of conductive threads for co-planar devices. While TransPrint can be used to create co-planar devices it increases the steps required to fabricate a display and the chances of human error, hence the need to create a solution that minimizes these. Furthermore, where TransPrint require several manual steps to fabricate a display, increasing the chances of misalignment during the process, ECPlotter aims at reducing these by both printing and curing as part of the entire printing process. Because of this, fabricating a display with ECPlotter only takes between 30 minutes to 2 hours enabling rapid iteration making it ideal for prototyping electrochromic displays.

Thirdly another approach was investigated, aimed at using consumer level ink-jet printers to print the conductive and electrochromic materials without the need to print each material separately. By printing each material separately the substrate will have to be re-entered into the printer tray for each required print thereby increasing the chances of small misalignment's between the prints. When printing complex and precise designs with conductive traces in the millimeter range, misalignment's have a detrimental effect on how complex a design can be. Therefore, the need to create a solution where this is not required. Previous research has shown that both conductive and electrochromic materials can be printed using consumer printers, however, in this thesis those results where not reproducible.

To answer R2, several examples are contributed either with the fabrication methods or through specific electrochromic prototypes where the various application scenarios shows the possibilities of how to utilize the technology. These prototypes range from very simple displays with limited functionality to more complex and integrated prototypes exemplifying a small array of the capabilities. The application scenarios are divided into three categories; interactive prototypes, art and decor, and teaching. For interactive prototypes the examples show how the displays can be driven by prototype boards made specifically for novices that wish to learn electronics and programming. For art and decor it is shown how traditionally printed graphics can be combined with electrochromic technology to generate changing or interactive art and how the transparency can be used to alter an environments feel and mood. The potential of creating transparent electrochromic devices is used to add interactive elements to otherwise static prints. For teaching the electrochromic fabrication is shown to be useable in Makerspace settings for teaching in STEAM context. Each of the categories and the examples presented elucidate different technological aspects of electrochromic displays thereby helping new comers create ideas and find inspiration, further democratizing the technology.

While electrochromic display technology has existed and been researched for more than four decades and multiple colors have been shown to exhibit electrochromic behaviour, so far only the color blue is suited for manual fabrication by novices as it is not toxic or require expert knowledge to fabricate with. This puts a limit to the creative possibilities of the interactive graphics one is able to create using the technology. When more non-toxic electrochromic colors are being made available further studies should examine whether the current fabrication methods needs to take into account any change in the design, printing or fabrication of the new colors. There might be changes in power required, thickness of material or distance between electrochromic fields between different colored electrochromic materials or other requirements.

While it can be argued that both the method ECPlotter and inkjet printing Prussian Blue non-conductive electrochromic ink is quick and provide fast iteration times there are still limitations with both of these processes. ECPlotter requires a custom printer that has limited print sizes and is still not as precise as inkjet printing, whereas printing non-conductive electrochromic ink requires a conductive substrate limiting not only the print quality, the maximum display size, but also the range of substrates electrochromic displays can be produced on. To enable prototyping displays with similar print quality as when printed with professional equipment more research in inkjet printing conductive electrochromic materials with consumer printers is required. Only inkjet printing can provide the precise printing capabilities of professional electrochromic fabrication equipment at low cost, therefore, there is a need for more research in finding the right combination of conductive and electrochromic ink that will work with one printhead without destroying it and with the ability to print the required amount of electrochromic material in one pass. Not only will such a combination enable printing on a wide array of both conductive and non-conductive substrates, it will also enable easy prototyping of co-planar displays while at the same having the precision and quality of a display printed on professional equipment at high printing speeds. Furthermore, inkjet printing is a household technology that most people have either experience with or are aware of, which means that by enabling inkjet printing the designs will add a large step in democratizing the technology.

Printing the designs are only one part of fabricating electrochromic displays, so even if a solution was found for inkjet printing both conductive and electrochromic materials, there is still a need to find a solution for applying electrolyte to create a fast, precise and low cost method where all materials are added to the substrate using hardware. One possible method would be to investigate or develop an electrolyte which could be inkjet printed, or a hybrid printer could be developed where e.g. electrochromic and conductive is inkjet printed and when ejected from the printer, it is ejected directly into a custom attachment that first heat cures the ink, then applies electrolyte and then cures the electrolyte. This hybrid solution would be able to fully print and cure a display where after the process is finished all that is required is powering the display.

Another area of electrochromic research that has not seen a lot of output from a fabrication point of view is in electrochromic fabrics. There are few examples where e.g. fabric has been soaked in electrochromic material so the entire patch of fabric is color changing and another example presents a screen printed graphic on fabric and then use transparent overlay to encapsulate the printed area making it rigid and remove the usual softness of the fabric [2]. While ECPlotter is able to print on polyester there were still some limitations to printed display with it being slower than usual displays and required higher voltages. Also it was not possible to print on other types of fabric that has a higher degree of soaking such as e.g. cotton and wool. One path of research could investigate whether it would be possible to pre-print a coating on the fabric before printing so there would be minimal soaking of the electrochromic material into the fabric possibly reducing the resistance. Also research in a semi hard transparent electrolyte gel would work well in combination with previous suggestion for electrochromic fabric. The electrolyte gel would provide encapsulation while also provide the necessary ionic conductivity for the electrochromic material. If these suggestion were to be solved it would open a new branch of electrochromic research where color changing fabric or color changing designs on fabric would become a reality with relative ease.

In Section 2.1 it was described that for a technology to be usable in personal fabrication a certain level must be reached in four categories [1]. *Hardware and materials* must become more consumer friendly, *Domain knowledge* must be provided in an easy to understand way for non-experts, *Visual feedback and interactivity* must be presented and potentially alleviate *Machine specific knowledge*. To summarize the conclusion, the contribution of this thesis will be held up against those categories.

The TransPrint toolkit requires low-cost off-the-shelf hardware (screen printing kit or inkjet printer) and an ink kit providing all the hardware and materials required for fabrication electrochromic displays. While screen printing is not as well known as inkjet printing it can be argued that the technology is still consumer friendly because it does not require extensive knowledge to learn or utilize. With this in mind it can be said that the *hardware and materials* for fabricating electrochromic displays have become consumer friendly.

The accompanying software and online guides for both TransPrint and ECPlotter and the contributions presented in Chapter 4 provide knowledge that enable non-experts to relatively easily design and fabricate displays. The software and online guides provide the necessary knowledge to print good quality displays such as which frames to use for screen printing and which printer settings to use for inkjet printing. The contributions in Chapter 4 provide examples of how to control the displays, how they can be used and that they can be fabricated in arbitrary shapes. All of these contributions provide *domain knowledge* making it easier for non-experts to access the technology.

While the software provided in TransPrint create necessary parts for designs and has the ability to simulate the change between two sides in a vertically stacked design it can not provide the same simulation for a co-planar designs. The same restrictions are present in the software for the ECPlotter, however, this software provide other functions not available in the TransPrint software, such as automatically generating electronic connectors for the electrochromic fields in a co-planar design that can be visually dragged to position them. However, because neither of the toolkits are able to simulate state change for a co-planar design the *visual feedback and interactivity* category still needs work. Currently, the only way to understand if a co-planar display works as intended is to fabricate it and power it, which is the opposite of providing *visual feedback and interactivity* in the software.

As the TransPrint toolkit is a very manual process the *machine specific knowledge* required is minimal, whereas for the ECPlotter that automatically print all the required inks it is lot more relevant. However, despite TransPrint requiring minimal *machine specific knowledge* the online guides still provide the required knowledge to understand the different aspects of using this fabrication method. For the ECPlotter, the software provides the ability to control the print settings and see the effects of those settings in a print preview thereby presenting *machine specific knowledge*.

Democratizing of technology means the technology becomes more accessible to more people and for a technology to be usable in personal fabrication means it becomes consumer friendly, easy to understand, with software providing the required feedback for non-experts. Therefore it can be argued that the more a technology can be used for personal fabrication the more democratized it becomes. Despite, needed work in providing visual software for more complex displays such as co-planar designs the contributions of this thesis has moved the fabrication of electrochromic displays a fairly big step towards democratization.

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Part II

Papers - Fabrication Techniques

Paper A

TransPrint - A Method for Fabricating Flexible Transparent Free-Form Displays

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Abstract

TransPrint is a method for fabricating flexible, transparent free-form displays based on electrochromism. Using screen-printing or inkjet printing of electrochromic ink, plus a straightforward assembly process, TransPrint enables rapid prototyping of displays by nonexperts. The displays are nonlight-emissive and only require power to switch state and support the integration of capacitive touch sensing for interactivity. We present instructions and best practices on how to design and assemble the displays and discuss the benefits and shortcomings of the TransPrint approach. To demonstrate the broad applicability of the approach, we present six application prototypes.

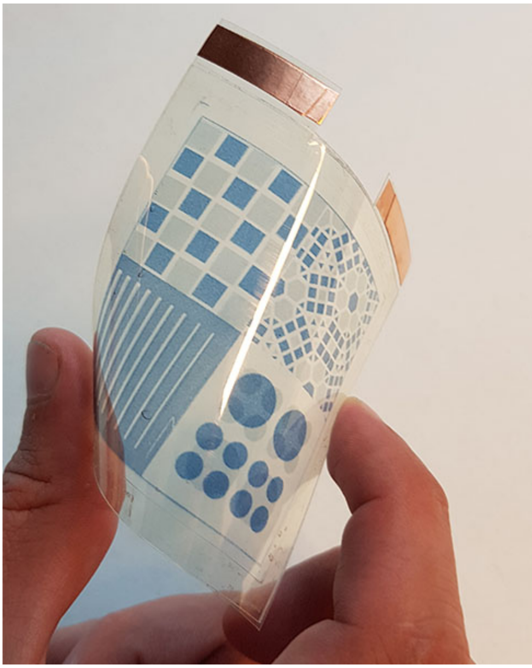

Fig. A.1: A display created with TransPrint.

1 Introduction

Decreasing price and the widespread adoption of mobile- and wearable devices have driven a dramatic increase in the amount of digital displays we encounter in our everyday lives. However, our environment still contains far more non-digital printed graphics, such as labels, signs, posters and books, than digital displays. Static text and graphics printed on paper and other objects, has been one of our major information sources for many years, and will continue to be so. Whilst in many applications, digital displays aim to emulate the properties of printed graphics, they are limited to a rigid flat rectangular form factor. This limitation restricts the possibilities to seamlessly integrate such displays into our surroundings.

Recently, the field of printed electronics has developed to the point at which thin and deformable interactive prototypes can be created at low cost, e.g. as design prototypes [1–3]. Prior work has focused on extending printing methods to create interactive materials such as flexible touch sensors, thin-film displays and even haptic feedback [4–7]. Especially, printed electronics displays have the potential to overcome the limitations of current digital display technologies, enabling more interactivity and new form-factors. Moving away from the square pixel-based architecture, which is dominant in today's display technologies, has been highlighted as a key factor to deliver truly ubiquitous technologies [8].

In this paper, we present TransPrint, an adaptable method that enables the production of flexible, transparent displays in highly customizable shapes by the maker community and other non-experts (see Figure A.1). TransPrint is based on electrochromism (EC), i.e. the property of materials to reversibly switch their optical properties, e.g. colour, through electrochemical oxidization. For TransPrint, this switch is between near-transparency and a dark blue opaque colour.

One of the key traits of displays based on electrochromic systems is that they are non-light-emissive. This distinguishes them from LED and electroluminiscence (EL) based displays [4, 6]. Given the negative impact of artificial light on human sleep patterns [9], this property is particularly beneficial for ubiquitous always-on displays, e.g. as part of Internet of Things (IoT) solutions. Together, the properties of TransPrint displays enable smart solutions that are embedded to the existing objects and surfaces of our environment, fulfilling Mark Weiser's vision of technologies that "weave themselves into the fabric of everyday life" [10].

While EC based displays have been well established and most characteristics of the different materials have been well investigated in the past, constructing these displays usually required laboratory settings [11]. With TransPrint we present a method that allows non-experts to produce EC based displays with commercially available materials. We present two ways of printing such displays using either screen-printing or ink-jet printing. Both methods are rapid, inexpensive, and only require a limited amount of hardware and technical knowledge. We show how to integrate these printed displays with static printed elements as well as new application scenarios stemming from the unique traits of TransPrint displays. Furthermore, we discuss how support for capacitive touch input can be easily incorporated. With this we hope to enable the community to adapt such displays and embed them in future research e.g. in the realm of printed electronics for interaction.

In this paper, we firstly discuss related work in the fields of printed electronics and displays, focusing on electrochromic systems and transparent displays. We then provide background on the operation of electrochromic displays in general and describe the TransPrint approach to design, print and assemble displays. Following this, we present an analysis of the key characteristics of the created displays. Finally, we present a set of application cases that demonstrate the possibilities of TransPrint displays.

2 Related Work

2.1 Printed Electronics Prototyping

Recently, an increasing amount of research has focused on using printed electronics in Human Computer Interaction (HCI) and UbiComp applications. Printed electronics allow the fabrication of thin and deformable electronic systems that can cover large areas and be integrated with other materials, thus challenging our traditional view of electronic circuits as flat and rigid [3], to the level of printed circuits for temporary rub-on tattoos [12]. Initial work conducted by Gong et al. leveraged ink-jet printed conductive materials for a wide variety of sensing applications [13]. Savage et al. introduced the Midas platform enabling the fabrication of custom touch sensing circuits utilizing vinyl cutting [14]. Following on from this, Kawahara et al. proposed a method to print circuit patterns designed using standard inkjet printers and software [2]. This method has been adopted to create a wide variety of different applications such as e.g. customizable touch sensors [15, 16], which can be cuttable [5], epidermal pressure sensors [17], deformation sensors [18] and even energy harvesting devices [19]. Recently Kato et al. used double-sided conductive ink printing to fabricate paper gloves that deliver electrical stimulus to create a pseudo-tactile sensation [7]. Olberding et al. combined many of these fabrication and sensing mechanisms with actuation capabilities into their Foldio approach [20], which Wessely et al. recently extended, to re-usable origami style elements [21]. Furthermore, there are even self-actuated paper prototypes that can be printed using conductive PLA [22].

A variety of different approaches to print these new materials have been presented, the most common being inkjet printing and screen-printing. Recently hydro-printing – printing via water transfer – has been employed to print touch screens on highly curved organic geometries [23]. Kuznetsov et al. analysed the potential of screen-printing as a DIY fabrication technique for embedding interactive behaviour onto a range of substrates [24]. They conducted workshops in Science, Technology, Engineering, Arts, and Mathematics (STEAM) contexts and found that it has a relatively low barrier to entry for smart material fabrication and supports collaboration and creative engagement.

Building on these previous approaches, TransPrint employs inkjet and screen-printing in the creation of our displays and aims to enable the combination of printed EC displays with other printed electronics prototyping techniques. Hence, enabling easy integration into wider printed electronics prototyping pipeline.

2.2 Thin Film Displays

A major distinction when it comes to thin film display technologies is whether the display is pixel-addressable such as OLED and E-Ink, or a graphical segment-based display in which only predefined shapes can be switched. Although the second category offers less visual dynamicity, it provides advantage in other areas, such as ease of fabrication and possibility to create displays in a variety of shapes and forms. Common technologies to realize thin film displays are e.g. ultraviolet [25], thermochromism [26, 27], electrolumiscence (EL) [4, 6, 28] and electrochromism (EC) [4, 29, 30], each having relative advantages and disadvantages. Ultraviolet-based displays require an additional light source and can suffer from low visibility in daylight conditions. Thermochromism is hard to control, due to the need for exact temperature control and the potential influence of ambient temperature. EC and EL displays are easy to fabricate at low-cost, are flexible, robust and low-power consuming. EL displays have a relatively long lifetime of up to 50,000 hours and, in comparison to EC, have faster switching times [6], making EL suitable for lighting applications [6, 31]. (Switching time here refers to the time it takes to switch from on state e.g. an off state where nothing is shown to another state where something else is shown). Different techniques have been proposed for the production of EL displays, such as cutting segments from a larger EC film [32], and screen- and ink-jet printing the substrate layers [6]. Olberding et al. demonstrated the possibilities of such displays with a design space that included different materials as well as a variety of application cases [6]. Additionally, screen-printed EL displays can be integrated with textiles [33]. Klamka and Dachselt extended the EL design space with their exploration into the possibilities of added pen interaction [4]. EC-based displays have several promising properties, for example, they can hold their display content for an amount of time without a battery, like e-ink displays. As with e-ink displays, they do not emit any light themselves and they have a comparably slow switching time between states. Previous work on EC displays investigated the capabilities for mass-manufacturing [34], manual manufacturing processes [29], and even developed multi-layered colour displays [30]. One of the main application cases for electrochromism so far are smart windows [35–37], whilst, more recently, other HCI applications have been explored. Klamka and Dachselt used an EC-based 8-segment display in their IllumiPaper prototype and Vyas et al. used an EC-based display that changed opacity with the increasing dust level of a vacuum cleaner [4, 38]. With TransPrint, we extend this line of work by presenting a fabrication process that enables non-experts to produce such displays and demonstrating the capabilities of EC based displays for a wider range of mobile and wearable UbiComp and HCI prototypes. Compared to previous work, we specifically provide detailed instruction on the design, printing and assembly processes for transparent EC displays, which are based on commercially available materials and can be fabricated in non-laboratory settings with simple prototyping equipment.

3 Electrochromic Displays

Electrochromism is the capability of some materials to reversibly change colour stimulated by redox reactions. This means that EC materials can change their optical absorption characteristics or colour when an electrical voltage is applied. A variety of different materials exist that can switch between different colour combinations and intensities. For TransPrint we are using the PEDOT:PSS (the chemical name poly(3,4-ethylenedioxythiophene) polystyrene sulfonate) mixture for printing, which can change its colour from nearly transparent to a darker blue. The PEDOT:PSS mixture exhibits EC properties because it is electrochemically active which makes it suitable as electrodes in EC displays and operates at low voltages (1-5 volt). Additionally it takes few seconds (< 3s) and requires low current draws (< 3mA) to switch a 5x5cm display fabricated with PEDOT:PSS. However, one thing to note is switch time and current

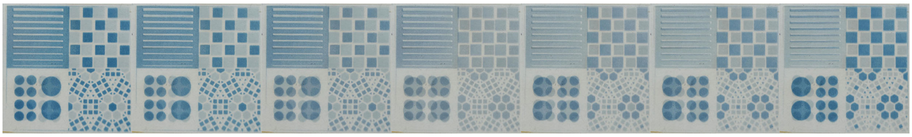

Fig. A.2: A displays switch from one state to the other. Left side shows one side fully switched, middle balanced state and right the opposite fully switched.

draw heavily depends on size and graphics design (amount of PEDOT:PSS used).

EC displays have several characteristic properties that enable a variety of applications [11]. They exhibit open circuit memory where its state stays the same when there is no short circuit, similar to electrical batteries, and can maintain their optical state and electrical charge for extended periods of time while drawing comparably little energy. This means that once the display reaches the desired visual state, no further energy is required to maintain the state. Energy is only needed to create a state change. The optical absorption (or in practice the strength of coloration) can be calibrated and set to any level between the states of minimum and maximum absorption, see Figure A.2. Compared to EL displays, the optical state transitions of EC displays are slow, typically lasting a few seconds, depending on physical dimensions and used materials. While some EC materials can take tens of minutes to switch, the PEDOT:PSS employed for TransPrint switches in less than 10 seconds even at A4 size prints. EC displays do not emit any light; they only change the amount of light they absorb. Given that the increasing amount of artificial light in our daily life – especially from digital displays – has been shown to lead to disrupted sleep patterns and increased sleep deficiency [9], the non-light-emissivity of EC displays presents an opportunity for more ubiquitous display deployment.

To date, EC technology has predominantly been used in windows and smart glass, enabling dynamic change of optical and thermal characteristics [11, 36, 37]. This is because the change of the absorption happens on an atomic level and therefore allows EC windows to switch without visible haze [39]. Recent advances have shown EC to be usable as an anti-counterfeiting method by applying electrochromic materials to paper [40]. While EC is a rather old and well-established technology in the field of organic chemistry, it has so far mostly been neglected for HCI research [4, 37, 38]. One possible factor for this is the problem of fabricating such displays, which we try to overcome with the TransPrint method.

A functioning EC display is composed of the following components: two conductors (electrodes) each connected to a field of EC material or 'ink', and electrolyte which separates the two fields of EC material (see Figure A.3). The conductors create an electrical circuit by allowing electrons and ions to move when an electrical current is applied through the EC material. The electrolyte is a gel substance with electrically conductive properties and is responsible for the ion exchange between the two fields of EC ink when a voltage is applied at the conductors. Insertion or extraction of ions into the EC ink changes the optical characteristics through reduction and oxidization, and as little as 1V is sufficient for this change to occur. An EC system needs two fields of EC ink that are connected to two different conductors so that an exchange of ions from one field to the other can happen when a voltage is applied. One field will be oxidized

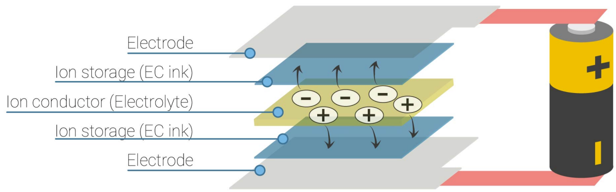

Fig. A.3: Composition of vertical stacked electrochromic technology.

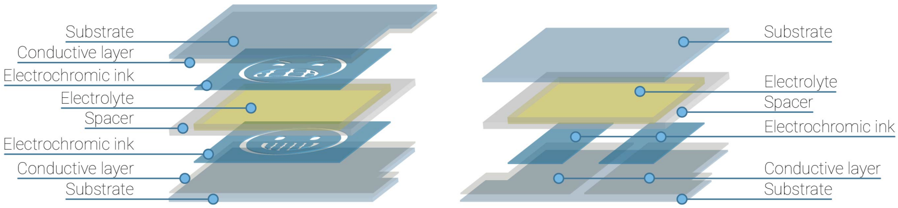

Fig. A.4: Composition of electrochromic technology. Vertical stack (left) illustrates how electrochromic ink is printed on two separate PETITO layers whereas coplanar (right) shows how the ink is printed on the same PET-ITO but with the ITO layer separated into isolated fields.

while the other is reduced, and vice versa when the polarity of the voltage is reversed. Visually, this redox causes one EC field to become transparent whilst the other gains colour. Alternatively, one of the EC ink fields can also be replaced by any other ion storage material that does not exhibit colour change on redox, as shown in Figure A.3.

While theoretically not needed for functionality, the display components need to be contained by elements that will insulate and protect them. Thus, a top and bottom substrate are required. To be able to observe the visual change, at least the upper substrate should be transparent. Typically, glass has been used, but more recently, polymer-based plastic e.g. polyethylene terephthalate (PET) and polycarbonate (PC) have been employed as well. In some implementations, the lower substrates can even be replaced with paper [41].

4 Prototyping TransPrint Displays

In this section, we present the design and fabrication process of TransPrint displays, which are transparent, flexible EC displays. This includes two alternative structures or stack designs, vertical and co-planar (see Figure A.4), a detailed description of the fabrication process using screen-printing and ink-jet printing as well as design considerations.

Firstly, TransPrint Displays can be produced in two different ways: either a vertical or a co-planar stack of the different elements. In the vertical stack all elements are stacked vertically, meaning both electrodes with EC ink are on top of each other divided by the electrolyte (compare Figure A.4 (left)). So that the ions would flow from the top layer EC ink through the electrolyte to the bottom layer EC ink or vice versa (when the polarity is switched). For the co-planar stack both EC ink fields are on the same layer with two separated electrodes (compare Figure A.4 (right)). This means that the ions from one of the EC ink fields to the other through the electrolyte. The main difference between these two construction methods is that in the vertical stack the ink fields e.g. can overlap while in the co-planar stack they must be next to each other.

To create the construction highlighted in Figure A.4 the TransPrint method uses the following materials:

- Substrate: PET-ITO
- Electrochromic Ink: Ynvisible EC Ink (based on PEDOT:PSS)
- Electrolyte: Ynvisible Electrolyte [42]
- Spacer Material: Double-sided tape 3M 9495 LE 300LSE

For TransPrint we selected to use transparent PET film as the substrates onto which displays are constructed. In the vertical stack configuration, one EC ink field is printed on both substrate layers, whereas in the co-planar stack, both EC ink fields are printed on a single substrate. In both cases the two EC ink fields each have their own conductor and are connected only by the electrolyte layer. The EC ink used in TransPrint displays is itself conductive, thus it is only required to configure the conductors to connect to the edges of the EC ink fields. However, to reduce potential design limitations and ensure consistent switching performance, in TransPrint we utilize substrates coated with a conductive Indium Tin Oxide (ITO) layer which is one of the most commonly used transparent conductors and is also used as the conductor on smartphone touch panels.

Thus, TransPrint utilizes PET film pre-coated with ITO (PET-ITO) as substrates. For the vertical stack, both base and top layer are PET-ITO whereas for the co-planar structure PET-ITO is used for the base layer and non-coated PET for the upper layer. When using pre-coated PET-ITO where the whole piece is one conductor (e.g. the Adafruit ITO Coated PET with a thickness of 175μm) for the co-planar stack, electrical separation of the two ink fields must be ensured, e.g. by scratching away the ITO coating from the PET to create a gap. Graphical display designs can be printed directly onto the ITO side of the PET-ITO using either screen- or ink-jet printing. The PET-ITO material used is a thin film, which can easily be cut to different shapes, increasing the options for customization and flexibility of the displays. To prevent electrical short circuits between the top and bottom layers, and to provide a container for the electrolyte, the PET-ITO substrate layers must be held apart.

In TransPrint this separation is created using double-sided adhesive sheets in which spaces have been cut out around the ink printed area, specifically 3M 9495 LE 300LSE, with a thickness of 170μm (see Figure A.5). The amount of electrolyte required is calculated as the cubic volume of the container that is created between the two substrates and the spacer. For example, a display with a 5x5cm area using the previously mentioned adhesive sheets give the container a height of 170μm and therefore require 0.425mL of electrolyte (5cm x 5cm x 0.017cm = 0.425 cm3 = 0.425ml). This means that the average amount of needed electrolyte is dependent on the size of the display.

Either Ink-jet or screen-printing can be used to transfer the graphical design onto the PET-ITO substrates. For rapid and precise prints ink-jet is optimal - however, it

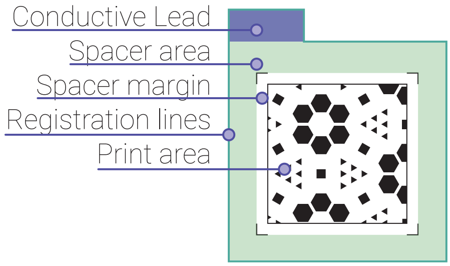

Fig. A.5: One side of vertical stack design example including spacer (green) and conductive lead (blue). A narrow margin is added between design and spacer material.

allows for less control over the amount of EC ink deposited during the printing process which can potentially lead to lower quality prints. For both, ink-jet and screen printing we used PEDOT:PSS based EC inks supplied by Ynvisible Interactive Inc . While not completely identical, we expect comparable results from PEDOT:PSS based inks supplied e.g. by Sigma-Aldrich . Screen-printing utilizes a stencil of the graphic design on a frame-mounted mesh to transfer the ink onto the substrate [24]. Screen printing meshes have different thread densities, depending on how much detail is required, or how much ink has to pass through it. Additionally, the type of emulsion used to create the stencil affects the print detail. As an alternative to using emulsion, stencils may be cut out from vinyl.

Figure A.2 shows the transition between the two maximum states of a vertical stack EC display, caused by the reversal of the polarity of the voltage applied across the display conductors. For this 5x5cm display the full transition takes approximately 2.5s. Applying power to the display for shorter times will place the display in an intermediate state where the maximum opacity is not reached. Switching time and required voltage are dependent on the EC design, size and used ink and electrolyte. For the Ynvisible EC-SC ink a maximum voltage of 3V is recommended, however the ITO layer on the PET-ITO will degrade if a voltage of more than 1.5V is used, which in turn sets the maximum voltage for driving the display. Given these low voltage levels, the displays can easily be controlled using e.g. an Arduino microcontroller and could be even activated using wireless energy sources such as NFC, as demonstrated by Dierk et al. [6]. Furthermore, the active operation temperature of these displays' ranges from -100°C to +100°C and they continue to be functional after structural damage (e.g. a corner cut off) if the two conductors are not creating a short circuit. The displays are also bendable up to 7.5mm radius (see Figure 1) while remaining functional. The bend radius is limited by the fact that the ITO layer on the PET-ITO will break with a lower radius and thus increase the resistance. This also means that the mechanical endurance of the displays when repeatedly bend is only dependent on the quality of the PET-ITO. A bend-radius of 0.75cm - 1cm has been shown to have no influence on the resistance of the PET-ITO [43]. However, not only the bend radius is increasing the resistance of the PET-ITO but also repetitive bending as it leads to micro cracks [44, 45]. Given results presented by Li and Lin it is expected that after ca. 300 bends with 17.3N strain the PET-ITO would reach a level were a significant increase in switching time would

Fig. A.6: Left: screen-printing frame with exposed design. Right: screen-printing of EC displays.

be visible and after 2000 bends being most likely be unusable due to the number of micro cracks [45].

Furthermore, it should be noted that the printing of TransPrint displays does not require a completely dust free work environment. Although any dust particles etc. that made it onto the materials during the construction process will be visible on the display, they will not impede the display's functionality. Nevertheless, it is advised to work in an as clean environment as possible and use gloves through the whole procedure to not leave fingerprints on the display.

4.1 Graphical Design

When designing the graphics for a TransPrint display several factors should be considered. Vertical stack structures have two layers overlaid on each other, allowing a large degree of creativity in how the finished display will look. In the co-planar structure, the EC fields should be next to each other, enabling the ions to move from one field to the other, placing more restrictions on the design. To partly address this limitation, opaque masks may be placed on top of the display, e.g. Klamka and Dachselt used a co-planar 8-segment EC display for their work, in which each segment in the display consisted of a pair of EC fields were used [4]. In this case, one field was the visible segment of the 8-segment display, whilst the other served as a masked counterpart to complete the Redox reaction.

If screen-printing is used, the frame count and emulsion determines the minimum size of both trace width and detail size, however there is no limitation for how big a trace or feature can be. The same applies when vinyl cutting is used to create a stencil, the accuracy of the vinyl cutter used must be sufficient for the level of detail in the design. Once the graphics have been developed, the design has to be finalized for print which requires adding registration lines for the spacer material (double sided tape) and connections for the electrodes (see Figure A.5). This step is especially important when designing for the vertical stack structure, as the conductive leads should be offset to avoid shorting the electrical circuit. If a vertical stack design uses superimposed graphics between the two layers, one side of the design should be mirrored to ensure it would be correctly oriented when assembled. The switching time of the display can be

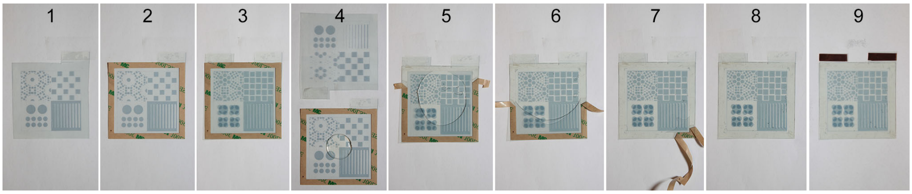

Fig. A.7: The different steps of the assembly process of a vertical stack TransPrint display.

affected by altering the balance of the amount of ink between the paired EC fields, e.g. if both top and bottom layer have an equal amount of ink for insertion and extraction of ions the switching time will be equal for both polarities. Altering this equilibrium allows designers to create interesting and alternative transitions in their designs.

4.2 Display Printing

The process of screen-printing EC displays follows the normal screen printing procedure and does not require any specific changes to the process (compare Figure A.6). In section 5.1 we discuss in detail the effect of different stencils and mesh counts. Most screen-printing equipment should be suitable for printing of TransPrint displays and, besides the graphical design of the fields, there are no limitations that affect the screen printing of EC ink compared to any other ink. When using ink-jet printing some details should be considered. Firstly, we recommend using a piezo-driven printer rather than a thermally driven one. As the EC ink is water based there is a risk that the heat of the thermal-driven printing alters the structure of the EC ink. Considering the amount of ink discharged, prior work recommends using the Brother brand of printers, as they have been shown to dispense larger amount of ink [2]. For our tests, we utilized a Brother MFC-J480DW with corresponding refillable cartridges, which provided excellent print quality. The Ynvisible ink-jet EC ink has to be filtered before use, to avoid particles clogging the print head. Overall, ink-jet printed displays have shown lower contrast ratios compared to screen printed ones. However, ink-jet printing provides the possibility to easily change and adjust the graphical design without the need to manufacture a stencil first. Therefore, it is very well suited for making rapid proof-of-concept prototypes. After the silkscreen or ink-jet printing process the ink, coated PET-ITO must be heat-cured for 2m - 3m at 120°. This is because the EC ink is water-based which should evaporate before the display is assembled. For this either a small oven or a heat gun with temperature control is recommendable.

4.3 Display Assembly

After the EC ink has been printed on the PET-ITO, the first step in the assembly is to cut the PET-ITO and spacer to size (Figure A.7(1)). If the cut lines did not get through the mesh during the screen-printing process, the negative mask can be used to mark where to cut. Afterwards the spacer material - double-sided tape - should be applied (Figure A.7(2)). To help aligning the layers, the base and top layers should align and taped to the cutting board at one side i.e. creating a hinge. This way the top layer can then be flipped over while maintaining alignment with base layer while the spacer is added to the base layer (Figure A.7(3-4)). The cubic volume of the spacer cut-out should be calculated to identify the amount of electrolyte required. Using a syringe, the liquid electrolyte is then applied as a blob in the middle of the cut-out in the spacer, and the top substrate layer is flipped back over to cover it (Figure A.7(5)). The electrolyte should then be gently dispersed to fill the spacer area using light pressure in a circular motion while at the same time removing the spacer protection as it is dispersed. Firstly, the electrolyte will disperse towards the spacer wall midpoints. However, before the electrolyte reaches the spacer walls midpoint, the top substrate layer should be pressed to the spacer ensuring it adheres, and preventing the electrolyte from being squeezed out. The electrolyte should then be eased into the corners of the space, ensuring it is evenly dispersed (Figure A.7(6-8)). Finally, copper tape is applied to the conductive leads to improve conductivity (Figure A.7(9)). Once the display is assembled, it should be cured under UV light for 25 - 30 minutes using a commercial 500W halogen spotlight. But basically, any lightbulb that emits UV can be used but will requires different times [42]. The UV curing process solidifies the electrolyte to film instead of a liquid, making the display more robust. While this step is not needed, it is recommended to ensure a longer lifetime as well as prevent short-circuits. A video overview of how to assemble the display can be found here: `https://youtu.be/mi0p2VBo41s`

4.4 Integration of Capacitive Touch Sensing

Through capacitive touch input TransPrint displays can also be made interactive. As TransPrint displays are comprised of different conductive layers it is possible to sense a finger touching the display surface using capacitive sensing [46]. Specifically, the PET-ITO substrate provides excellent conductivity to be used as a touch surface to e.g. control the colorization of the display. For our proof-of-concept evaluation, we utilized an off-the-shelf MPR121 touch sensor breakout board connected to one of the two PET-ITO layers of a vertical stack display. While the MPR121 has on-board touch and proximity sensing capabilities including auto calibration and configuration for optimal sensing, we found that using the default settings on the MPR121 did not have sufficient sensitivity and therefore changed the charge capacitance to 63μA instead of the default 1μA. After establishing the basic ability to sense touch, we proceeded to test the sensitivity of different regions of the display. Differences in response across the display area were found to be negligible overall if the ITO layer has not been altered. Through alteration of the ITO layer - e.g. through scratching it away and effectively dividing it into multiple parts – several touch points can be created. It should be noted that during switching, when power is being delivered to the display, touch sensing is not possible as the PET-ITO is being charged. Given that the display requires power for time periods of up to 2 seconds, this can be problematic. Therefore, we would advise to use time-multiplexing between power for switching the display state and sensing (similarly proposed by Olberding et al. [6]). The following cycle durations have been found working for the MPR121 and a TransPrint display: A display switch cycle of 10ms is followed by a sensing cycle of 5ms. This results in a frame rate of 67 Hz. This increased the time for a full display switch by 33

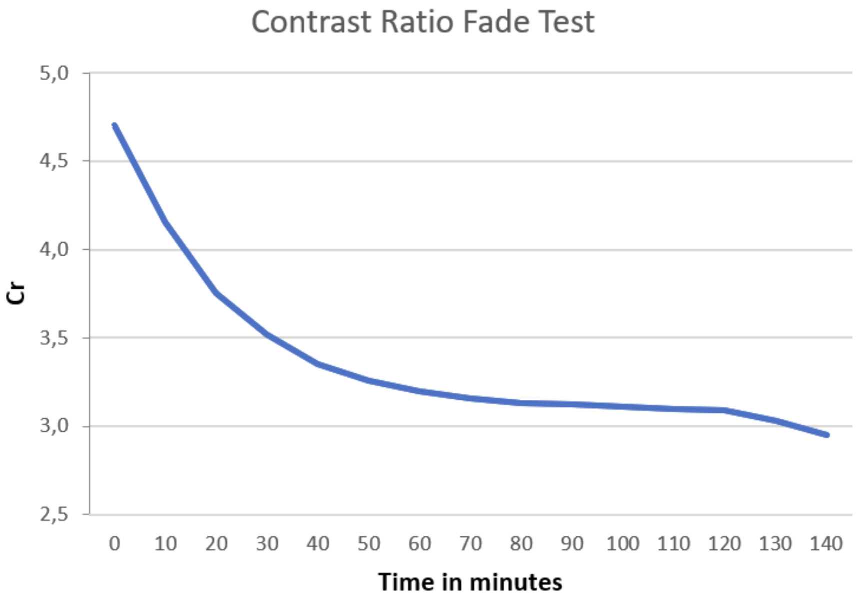

Fig. A.8: Development of contrast ratio after an ECdisplay has been switched to one state.

4.5 Display Contrast

One of the advantages of EC based displays is their relatively low need for power. Once the display has been switched (either oxidized or reduced) into one of its states, it will stay in this state for a certain amount of time, while slowly fading to the neutral state. To investigate this fading contrast, we switched a TransPrint display into one of its states and captured pictures with constant illumination every ten minutes. We used a Canon EOS600D camera connected to a Raspberry Pi to capture the pictures. To quantify the temporal change we used the contrast ratio as a measure. The contrast ratio is defined as the ratio of the brightest colour compared to the darkest colour that the display can produce [47]. Usually it is measured between white and black, but as we used blue EC ink, we measure the contrast between an area of the display placed on a white background and the darkest blue tone on the display. As no standardized method existed, we employed an approach similar to Gentile et al. [48] the W3C defined method from the Web Content Accessibility Guidelines (WCAG) [49]. The WCAG uses the following definition of contrast ratio (Cr) between the text and background colours:

$$C_r = \frac{L_1 + 0.05}{L_2 + 0.05}$$

where L1 is the relative luminance of the brightest colour, L2 is the relative luminance of the darkest colour for which $1 \geq L1 \geq L2 \geq 0$. The definition of relative luminance L corresponds to the Y component of the colour in the CIE 1931 XYZ colour space [47]. Given the above formula the maximum Cr is 21 and the minimum 1. The WCAG suggest a minimum Cr of 3 for websites to be easily readable [47, 48]. We repeated the fade test for 10 displays printed with screen printing using 80T frames and High Resolution - Diazo-Photoemulsion and calculated the Cr for these displays at 10-minute periods. The averaged fading can be seen in Figure A.8. Directly after the displays have been switched into one of their states, the Cr is very high at around 4.5 but after the first 20mins on average it already loses a significant amount of contrast, but nevertheless it stays above the minimum recommended Cr of 3 for over 2 hours. This demonstrates that TransPrint displays can retain an adequate contrast ratio for 2 hours before they need to be stimulated again. While this is not as lengthy as the retention time of e-ink displays [50], the possibility to fabricate them in a DIY manner and the ability to be transparent provides advantages that are unmatched by e-ink.

4.6 Display Lifetime

One of the important aspects of an EC display is its ability to switch between oxidized and reduced state and retain its visual details. However, this ability can fade after a number of switching cycles. Using a Canon EOS600D camera connected to a Raspberry Pi, 10 displays were subjected to a degradation test. The displays were switched 10000 times with a photograph of the display being taken every 100th switch. Each switch cycle consisted of a 2.5s time powered with 1.5V followed by a 2.5s rest period, followed by a powered cycle again of 2.5s with -1.5V and another resting period of 2.5s. During the resting period no power was applied. The displays did not exhibit any degradation and were able to fully switch after the completed test sequence. However, after 10000 switches the switching time needed to fully excite the display increased and to fully transfer to one state had increase to 3.5s compared to 2.5s prior to the test. The changes were visible after 4200 changes and linearly degraded. However, it should be highlighted that no changes in terms of contrast ratio were found if the displays were fully excited. These findings demonstrate the durability of the TransPrint displays but highlight that the switching time need to be potentially adapted over time. TransPrint displays only require power during switching; once the display transition is completed, continued electricity will permanently damage the display. At this point we would like to stress that the production of these displays is a manual process, the display quality can vary drastically, and detailed analysis of the displays would be subject to large deviations.

4.7 Power Consumption

EC based displays have a low power consumption and only require to be powered when switching between the different states of the display. However, the exact amount of energy consumed by an EC display to switch depends on a variety of different factors. The main factors are the size of the displays as well as the amount of ink that has been used. In addition, the amount used electrolyte and the quality of the ITO coating on the PET potentially affect the energy consumption. To give an estimate of the power consumption, we measured the consumption of a set of displays. We used an Agilent 34450A Multimeter and the corresponding software for it. We tested three different displays; 5x5cm Evaluation Design printed using Ink-Jet printing, 5x5cm Evaluation Design printed using an 80T Frame with High Resolution emulsion, and a 10x10cm honeycomb design (compare Figure A.10 printed using an 80T Frame with High Resolution emulsion. For each of these displays we used a switching time that was just long enough to fully complete the visual transition. We then calculated the average power requirements over five switches for each display. For the ink-jet display, the switching time was 1.1s, with an average current draw of 2.72mA, resulting in a power consumption of 4.3mW per switch. The screen-printed 5x5cm display took 2.4s to switch and had an average current draw of 2.6mA, which resulted in a power consumption of 3.8mW. Lastly the screen-printed 10x10cm display had a switching time of 5.1s and an average current draw of 4.9mA, resulting in a power consumption of 7.8mW. These values well demonstrate the low power consumption of TransPrint displays.

5 Best Practices

In this section, we report on best practices for producing high-quality EC based displays using the TransPrint method. Our overview of best practices and expected outcomes are based on the authors' experiences from printing several hundred displays using this method.

5.1 Print Quality

As the amount of EC ink applied to the PET-ITO effects the maximum levels transparency and colourization of the final display, here we provide an overview of the influence of mesh count and vinyl stencil placement in terms of ink dispersion. For detailed prints it is important to ensure that high details are retained from the original digital design through to the final print. As the emulsion type dictates the amount of detail retained during the exposure, we investigated two different types of emulsion. Furthermore, we also give an overview of results that can be achieved of vinyl stencils, which are a viable option for screen-printing. For emulsion-based prints, the digital test design was printed to fill an A4 exposure film. An example of the digital design for test and assembled display in balanced and powered state can be seen in Figure A.9. Photographs of the displays were taken before and after applying power (1.5v and -1.5v). To keep to the off-the-shelf viability of fabricating EC displays we bought a screen-printing starter kit that contained a 55T frame, hybrid photo-emulsion and press. A starter kit of this kind is the fastest way to get into screen printing as it contains all the materials required to get started. Additional 80T and 120T frames and a high-resolution emulsion were bought for testing. All prints were made using 125μm PET-ITO (40-60Ω), 230μm double sided tape sheet spacer and Ynvisible EC-SC ink and electrolyte.

The screen-printing parameters compared were:

- Frame mesh count (55T, 80T, and 120T Frame)
- Emulsion type (FLX Screen - Hybrid-Photoemulsion and High Resolution - Diazo-Photoemulsion)

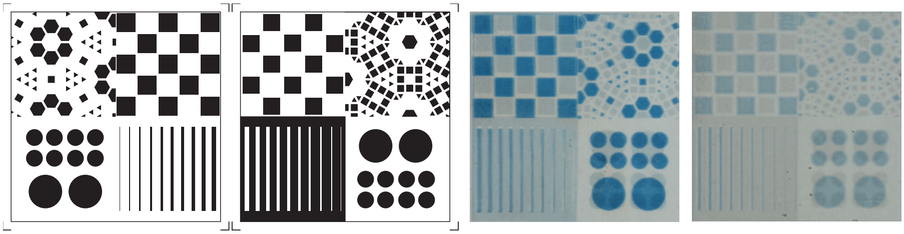

Fig. A.9: Left: digital design used for evaluating different parameters during screen-printing. Right: difference between displays printed using a 80T frame with high-resolution emulsion and inkjet printing.

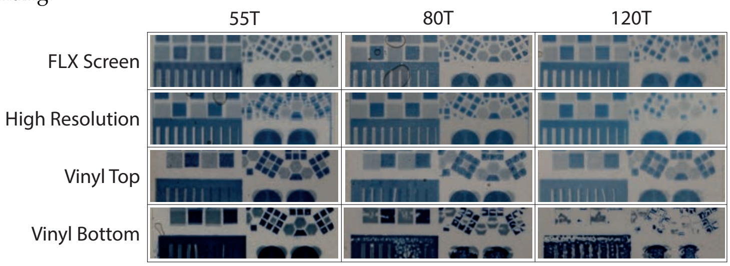

Fig. A.10: Images of powered displays arranged by thread count and stencil type.

- Vinyl stencil placement (On bottom of mesh and on top of mesh)

There is a difference in the preparation time between using vinyl stencils or emulsion stencils. While, emulsion requires several hours of drying and washing out, as well as exact exposure when the prints are transferred from the negative, preparing the cut-out vinyl requires a lot of manual labour depending on the amount of details that have been cut out. Depending on ones' knowledge of these techniques, times can vary. Nevertheless, both approaches will take longer compared to ink-jet printing. However, as the ink-jet ink needs to be more liquid than the screen-printing ink to be properly dispensed, ink-jet prints generally result in lower maximum colourization. Therefore, ink-jet printing is recommended for proof-of-concept prototypes; while screen-printed displays present a quality that are suited for longer-term usage.

Many factors affect the quality of the assembled display, including scratches and fingerprints created during the assembly process. However, here we disregard these production defects and specifically focus on the quality of the print regarding transparency, colour, and detail. The following factors were noted as affecting the display print quality:

- The thread count of the frame has a very eminent effect on the maximum transparency and colourization of the displays, see Error! Reference source not found.. A lower thread count will allow for a higher ink dispersion onto the PET-ITO.
- The FLX screen emulsion produced consistently good results. The High-Resolution emulsion resulted in similar results in terms of the amount of inks dispersed but with slightly higher details. Using 80T or 120T with high-resolution

emulsion produced the best results in terms of details and transparency.

- When the vinyl stencil was mounted on the top of the mesh, the results are comparable to the FLX screen emulsion print. However, due to the limits of a vinyl cutter, fewer details are possible. For a vinyl stencil placed below the mesh, only a thread-count of 55T produced prints of viable detail. However, the amount of ink dispersed was so high that the ink in its reduced transparent state was still strongly visible. The other two thread-counts consistently produced unusable results.
  A general challenge with the vinyl stencil was that during the transfer of the vinyl to the frames small standalone details can easily fall off.

5.2 Discussion

Transparency

An important characteristic of TransPrint displays is their transparency, and we experienced different levels depending on the printing process and materials used. One of the main influencing factors is the used PET-ITO. While the aforementioned Adafruit PET-ITO only has a very thin layer of ITO and is therefore highly transparent, other PET-ITO supplies we tested created a visible yellowing of the displays. The electrolyte [42] on the other hand has very little influence. Thinner layers of EC ink result in higher transparency when the ink is in a reduced state, but consequently result in a lower opacity when excited. Depending on the application case for the printed display, different approaches to printing will be optimal. For example, in a case where only limited transparency is needed but high colourization is required, a lower thread count and perhaps a vinyl stencil should be used to print the display. If the display requires a high transparency, a higher thread count with using screen print emulsion or even ink-jet printing should be favoured. Being able to vary the thickness of the layer by utilizing different mesh counts in the screen-printing process allows for more diversity in the design. The usage of vinyl as a stencil material is possible, however it should be placed on the top of the frame and a frame with a higher thread count should be used to get more usable results. Moreover, vinyl stencils only work acceptably with low detailed graphic designs. The high amount of ink dispersed when vinyl is placed on the bottom of the screen is most likely due to the thickness of the vinyl allowing a larger amount of ink to be deposited.

Ease of Design and Fabrication

A major challenge in the design of TransPrint displays is that the designer will only know how a display transition will look like once the final print is done. So far, no software to simulate and visualize these changes exists. Especially, in vertical stacks, where the printed layers are on top of each other, the maximum transparency of one layer can still influence the visibility of the other layer depending on the way they have been printed. Also creating a design where the amounts of EC ink in each field balance, to ensure optimal performance, can be challenging when designing such displays.

For smaller displays of less than a 9cm display diagonal, the production can be relatively easy managed by a single person. For larger displays with a larger diagonal

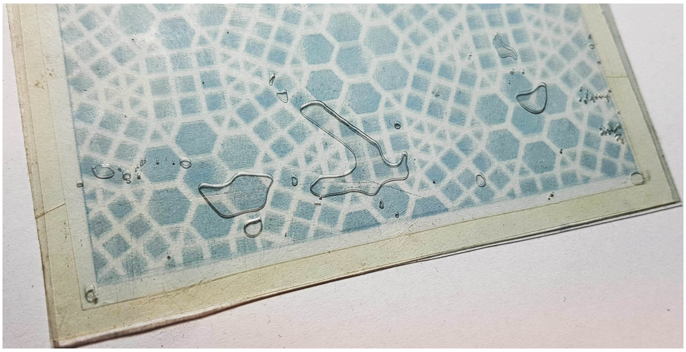

Fig. A.11: Example of 10cm x 10cm display assembled by one person with air bubbles in the print.

size, it is helpful to have a second person available during the display assembly to help avoid bulges and misalignment of the PET-ITO on the spacer material. Such assembly faults can create areas where the two ITO layers touch, thereby creating a short circuit in the display. Air bubbles in the electrolyte during assembly is another potential problem. Such bubbles can be partially alleviated by applying a circular motion when spreading the electrolyte, slowly distributing the electrolyte and creating a seal by pressing the PET-ITO firmly onto the spacer. However, for bigger displays the difficulty of this fabrication step increases and air bubbles are easily introduced (see Figure A.11). Nevertheless, there is no limit to the potential size of displays produced with the TransPrint method. However, larger displays have a significant higher switching time, e.g. an A4 printed display takes between 8 and 10 seconds.

While it is theoretically possible to create matrix displays using electrochromic materials [29] as well as with the TransPrint method, we would argue that those are not the strong points of this method. Given the needed connections for the different fields it would result in proper distances between the fields which in turn would not be very aesthetically pleasing.

Co-planar and vertical stack

The two stack structures supported by TransPrint each bring advantages and disadvantages, allowing for a high diversity in types of displays. The vertical stack allows for superimposed graphics that can switch between the two layers. If an equal switching time is required for the display, both layers should have near the same amount of EC ink applied and the EC parts should be close together to allow the oxidization and reduction to happen as efficiently as possible. By adjusting the switching voltage level (in the range 0 - 1.5v), the amount of EC ink and the placement of the graphics opposite each other it is possible to create different visual effects during the display switching. For co-planar stacks, the design can be more challenging, as the distance between the fields can prolong the switching time drastically. This can be used to create different switching effects but is normally not preferable. The main problem with this structure however is the need for non-connected conductors. While in advanced print processes,

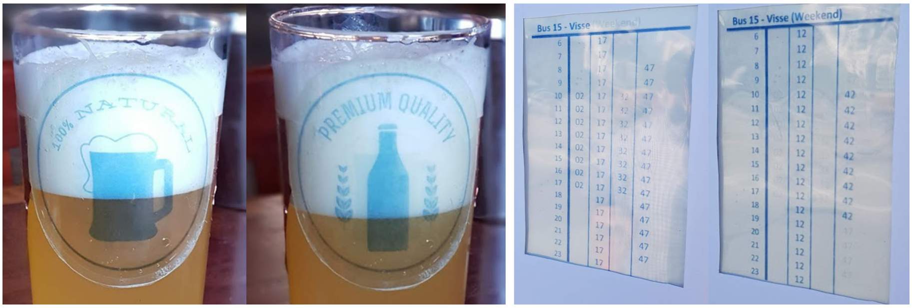

Fig. A.12: Application examples. Left: Changeable Logo. Right: Changeable time plan.

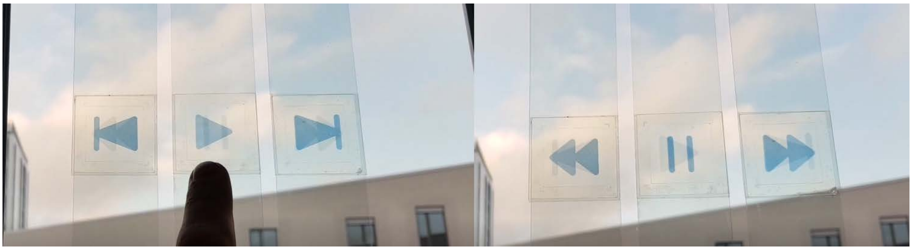

Fig. A.13: Application examples. Touch sensitive transparent buttons mounted on a window.

connections to the EC fields could be printed with conductive ink, instead of an ITO covered surface, this complicates the prototyping process drastically. Scratching the ITO of the PET-ITO surface is a faster method that can be applied after the EC ink is dried relatively easily but is more limited.

6 Application Examples

In this section, we present different application scenarios and ways to utilize TransPrint displays. We present six examples: a switchable logo, a context-adaptive timetable, touch-sensitive transparent buttons, an interactive paper map overlay, a wireless powered game card and interactive art. All the displays were printed using screen-printing with the following materials: 175μm PET-ITO, 130μm 3M spacer, Ynvisible EC-SC ink and Ynvisible electrolyte. As a limitation of the ITO, the maximum voltage for these displays is 1.5V unless otherwise stated. Higher voltages will degrade the ITO layer and eventually render the displays non-functional.

6.1 Switchable Logo

The first application case is a switchable logo for a glass. It demonstrates several of the unique capabilities of EC displays. It is a transparent and non-rectangular display - here in form of a circle - that is bent around a glass, see Figure A.12(left). The display is fabricated as a vertical stack and demonstrates a switch between two different graphics

Fig. A.14: Application examples. Left: Interactive Art. Right: Interactive Game-card.

Fig. A.15: Application examples. Interactive map overlay showing two different walking routes.

that, for example, can highlight different properties of a product - here the fact that the beer is Natural and Premium Quality.

6.2 Context-Adaptive Timetable

Static bus timetables typically have times printed for both weekdays and weekends on the same sheet of paper, taking more space than needed and confusing the reader. With a vertical stack design it is possible to print the two timetables overlapping and only show the relevant times when needed - for example the weekend schedule would only be shown on weekends, see Figure A.12(right). In this application, TransPrint displays have an advantage compared to EL and OLED displays, that they do not emit light and therefore are not subject to e.g. public legislation with respect to street lighting. This make them well suited to replace such paper-based public displays with more interactivity in the future.

6.3 Touch Sensitive Transparent Buttons

Several previous attempts have explored how transparent displays can support co-located work on a shared visual workspace [51–53]. However, these approaches often required complex display technologies such as LCD [53]. We believe that EC ink displays can be used for fast and cheap prototypes in this area as well. We printed a set of touchable buttons e.g. to control a media player (compare Figure A.13), that can be attached to a variety of surfaces. For touch sensing we use an MPR-121 breakout board, as described above. User interface elements that only express minimal change such as the here shown music player controls or simple switches are perfect examples how TransPrint displays can be used as interactive graphics that allow to be fitted on a variety of existing objects without altering their aesthetics significantly. However, if needed they can be used to alter the experience. For example, the different levels of transparency that EC displays offer can alter the appearance e.g. similar to the work of Lindlbauer et al. [54].

6.4 Interactive Paper Overlays

The last three application cases make all use of the same principle, they take advantage of the fact that TransPrint displays are transparent and can therefore be combined with already existing static printed materials. To demonstrate these retrofitting capabilities we created three examples: an interactive paper map overlay (see Figure A.15), a wireless powered game card and interactive art (see Figure A.14).

The interactive art piece aims to spur discussion around the possibilities of EC displays in the STEAM movement, as well as to demonstrate the creation of animations using EC transition times. The basis of this work is Kandinsky's Farbstudie Quadrate, where parts of the art have been cut-out and left white. These parts have then been printed on a co-planar stack EC display with two separate EC fields created by scratching the ITO layer so that it forms two electrodes. The assembled display is overlaid on the original art piece. Instead of using the usual switching voltage of 1.5V, a lower voltage such as 0.5 - 0.8V is applied, resulting in a slower transition time. This slow transition time creates the illusion that the art is alive and changing.

The low voltage requirements of TransPrint displays make it possible to power them using e.g. NFC, solar power or wireless charging. This could be applied similarly to the work presented by Dierk et al. [50]. We envision this could be used for example to create interactive game-cards in combination with technologies such as Project Zanzibar [55]. Our example overlays a skull on a regular game-card to indicate if the card has died in the game. For powering the game-card we used the MikroElektronika NFC Tag 2 click. A smart phone's NFC chip is providing sufficient power to change state of the display. For this display we used a vertical stack design, however we left out the second EC field and instead used the ITO layer of the PET-ITO substrate that was not printed on as the second ion storage.

The final example is an interactive overlay for a paper map, where e.g. bicycle riders can press a button to select a path that is then highlighted on the map. As with the interactive art piece we used a co-planar print with the ITO layers scratched to form two conductors. For such an outdoor situated display e.g. solar power with rechargeable batteries could be used to enable deployment the display nearly anywhere. Note also that no additional electrical wiring is required to provide interactivity.

7 Conclusion & Future Work

TransPrint is a method to print custom flexible transparent free-form electrochromic (EC) displays, which allows non-experts to easily create displays for use in HCI applications. The created displays are non-light-emissive, making them suitable for seamless integration into a variety of environments, without the disruptive light output of other display technologies. We have detailed the process to design and construct TransPrint displays, highlighting best practices and the benefits of alternative approaches. TransPrint displays are created using common screen printing or ink-jet printing methods, together with a lightweight assembly process. Capacitive touch sensing can be seamlessly integrated into the displays without the need for additional sensor wiring. The example TransPrint displays created maintain their display state without power for 2 hours, and have low-power consumption, requiring less than 4mW to switch state. The potential application space for TransPrint displays has been demonstrated by the construction of five prototypes. Our contribution extends the tool set available for the maker community enabling designers and creators to rapidly functional devices with a minimal overhead. For future work, we want to develop a software stack that will enable designers to simulate the visual qualities of the display before the display is printed. In addition, plugins that will support the designer while designing these displays e.g. by showing the area of the different EC ink fields would be beneficial. Furthermore, we want to explore more prototyping techniques.

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9 Supplementary Materials

A video overview demonstrating the printing and assembly process as well as the working prototypes can be found here: `https://youtu.be/xBwueuFHAk8` and here `https://youtu.be/mi0p2VBo41s`

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Paper B

ECPlotter: A Toolkit for Rapid Prototyping of Electrochromic Displays

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Abstract

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.

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 [1]. In such a future, every surface will become interactive. Besides integrated sensing possibilities (e.g., [2] and [3]), we will also see pervasive display surfaces where graphics that in today's world are mostly static will become interactive and context aware [4].

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 [5].

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 [5], 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]. 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's of the screen-printing process presented in [5], 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:

- a 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 [12] uses the heat generated from a laser to switch thermochromic materials from transparent to colored. PhotoChromeleon [13] 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 [14] 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 [15], SiliconeDevices [16]), applicable to large surfaces (Sprayable User Interfaces [17]) as well as curved object geometries (ProtoSpray [18], ObjectSkin [19]). In addition, researchers demonstrated how to fabricate displays of different visual complexity, ranging from simple shape, to segment, and matrix displays (PrintScreen [20], Amiraslanov et al. [21], Ivanov et al. [22]). While there is a large body of knowledge on how to fabricate electrolumiscent displays using screen-printing or inkjet printing (PrintScreen [20]) as well as spraying (Sprayable User Interfaces [17]), 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. [4]) 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. [23]). 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. [24], Iuliano et al. [25]), to ambient information and notifications (Müller et al. [26], Vyas et al. [27]), and privacy screens applied to transparent office walls (Telhan et al. [28]). So far, electrochromic displays have mainly been fabricated in a mass-manufacturing setting (Coleman et al. [21]). 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. [29]). TransPrint [5] 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 a makerspace by non-experts to produce their own display designs. For our research, we built onto this work but instead fabricate electrochromic displays using printed electronics.

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 [30]). Over the last years, inkjet printing of functional inks has seen many applications, from printing different types of user input elements (Cuttable Multitouch Sensor [31], Multi-Key Touch Input [32], Gong et al. [33], FoldIO [34]) to various output capabilities (Printed Tactile Display [35]). By using transfer paper as the substrate, inkjet printing can also be used to create displays on curved surfaces (SkinMarks [36]) and to create transfer layers for more complex fabrication processes, such as those based on hydrographics (ObjectSkin [19]). Recently, researchers also started to investigate how to inkjet print display elements. FunCushion [37] 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 [20], the authors used an inkjet printer to print the conductive traces for the display stack of electroluminescent displays similar to [30]. Building on this Khan et al. [38] 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

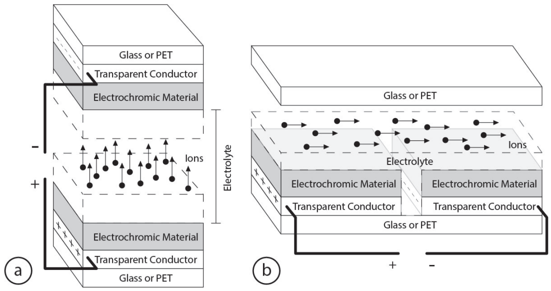

Fig. B.1: General representation of electrochromic displays. (a) Vertical stack: Ions move from the bottom to the top and vice versa through the electrolyte, (b) Co-planar stack: ions move from left to right and vice versa through the electrolyte.

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. B.1). Thus, stable electrochromic displays always need at 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 workstep. 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 [5] 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. B.1, 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.

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. This eliminates the need to move the substrate for curing in between each layer which were necessary in previous fabrication methods [5]. 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)

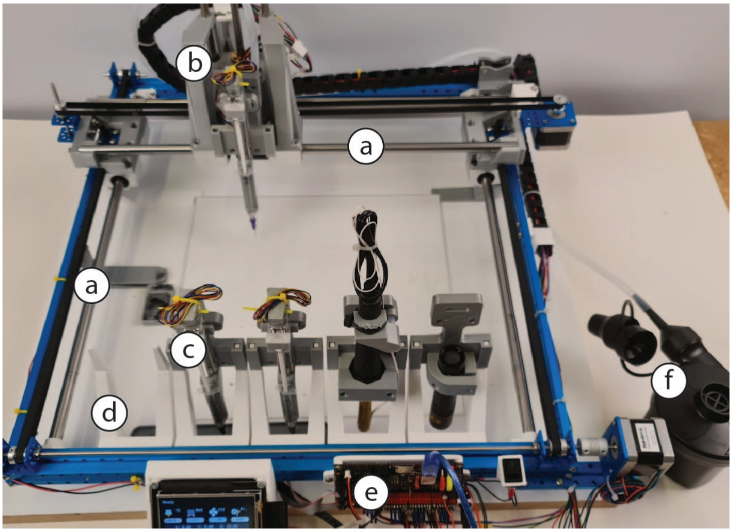

Fig. B.2: The ECPlotter hardware: (a) resized 12mm rods, (b) gantry with height control and tool changing capabilities, (c) syringe depositing tool, (d) tool holder, (e) new control board with display and (f) air pump.

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. B.2,a) to add more stability and the ability to support more weight. Second, the main gantry (Fig. B.2,b) was redesigned from the ground up to support height control and tool changing. Third, five tool holders (Fig. B.2,d) were added to the frame to support the required tools. Finally, for the control board (Fig. B.2,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 enables 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, 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.

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. B.3,a) provide easy snap-on and release of the tools using the built-in strength of the gantry's movement. To

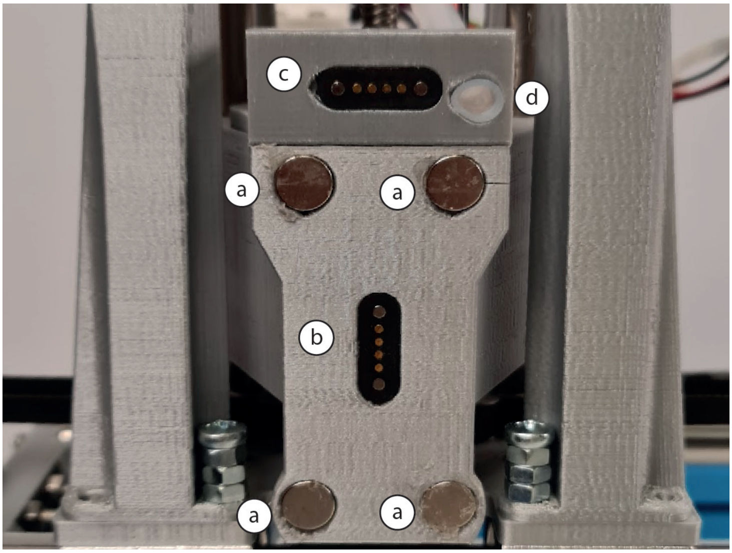

Fig. B.3: The printers gantry with (a) Neodymium magnets for connecting to the tools, (b and c) magnetic pogo connector for controlling tool stepper motors and powering the heat gun tool, (d) air hose for blowing air through heat gun tool.

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. B.3,b) and one at the top (Fig. B.3,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. B.2,c and d).

Syringe depositor tool: Depositing ink is achieved by a small linear stepper motor (Walfront, 12v rated, Fig. B.4,left,c) actuating a 1ml syringe (Fig. B.4,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. B.4,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

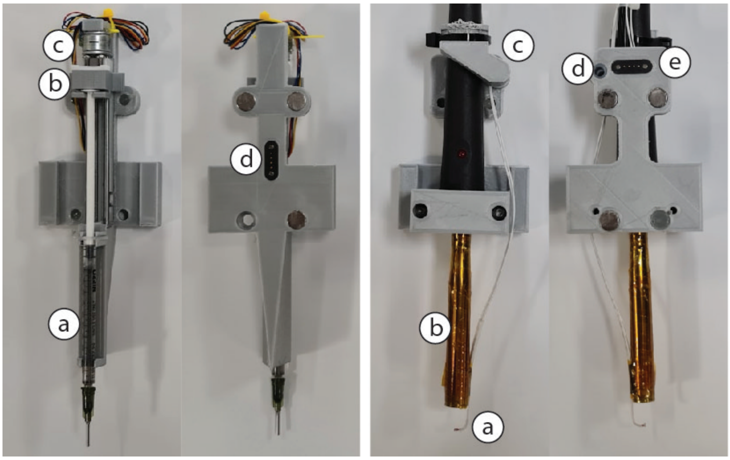

Fig. B.4: Two of our tools integral to the printing process. *Left:* The syringe depositor tool consisting of a syringe with an attached tip (a), a coupler connecting the stepper motor with the syringe (b) a small linear stepper motor (c) and a magnetic four pin pogo connector (d). *Right:* The heat 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).

rated, Fig. B.4,right,b), a thermistor for measuring the temperature (Fig. B.4,right,a), a custom designed air pump connector (Fig. B.4,right,c and d) and a four pin magnetic connector (Fig. B.4,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 (6mm internal diameter, Fig. B.3,d) from an air pump (Tenzo Electric, 280 L/min rated, Fig. B.2,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

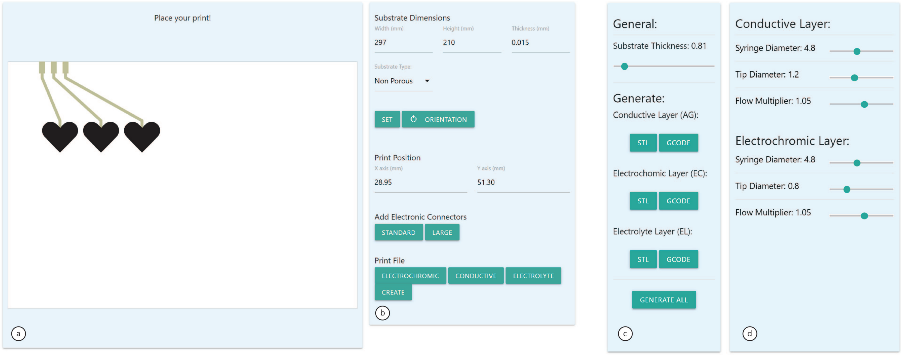

Fig. B.5: The simple and advanced parts of the toolkit application. (a) The interface to set the position of a simple print and the electronic connectors on the substrate. (b) Lets the user enter the dimensions of the substrate and whether it is porous or not. Further more this interface allows the user 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.

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 from the height of those models, the syringe diameter and tip diameter with a flow multiplier added to the calculation (Fig. B.5, 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. B.5,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. B.6,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.

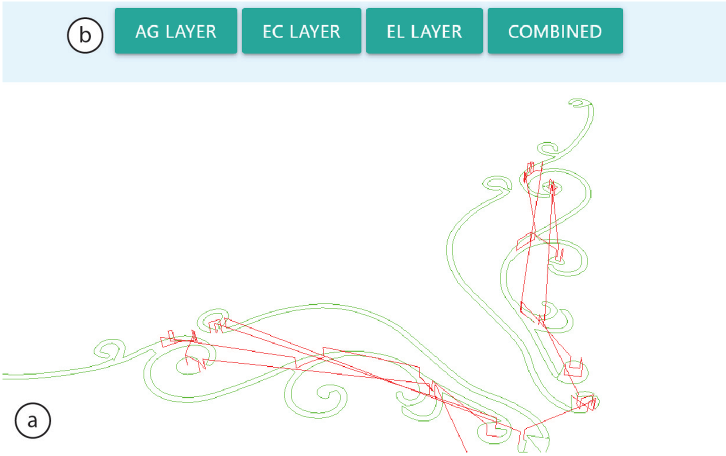

Fig. B.6: After generating a print file, the software presents the user with: (a) a preview of the toolpath generated and (b) an option to select whether to preview the individual layers or the full print.

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), 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

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

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 [5] 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.

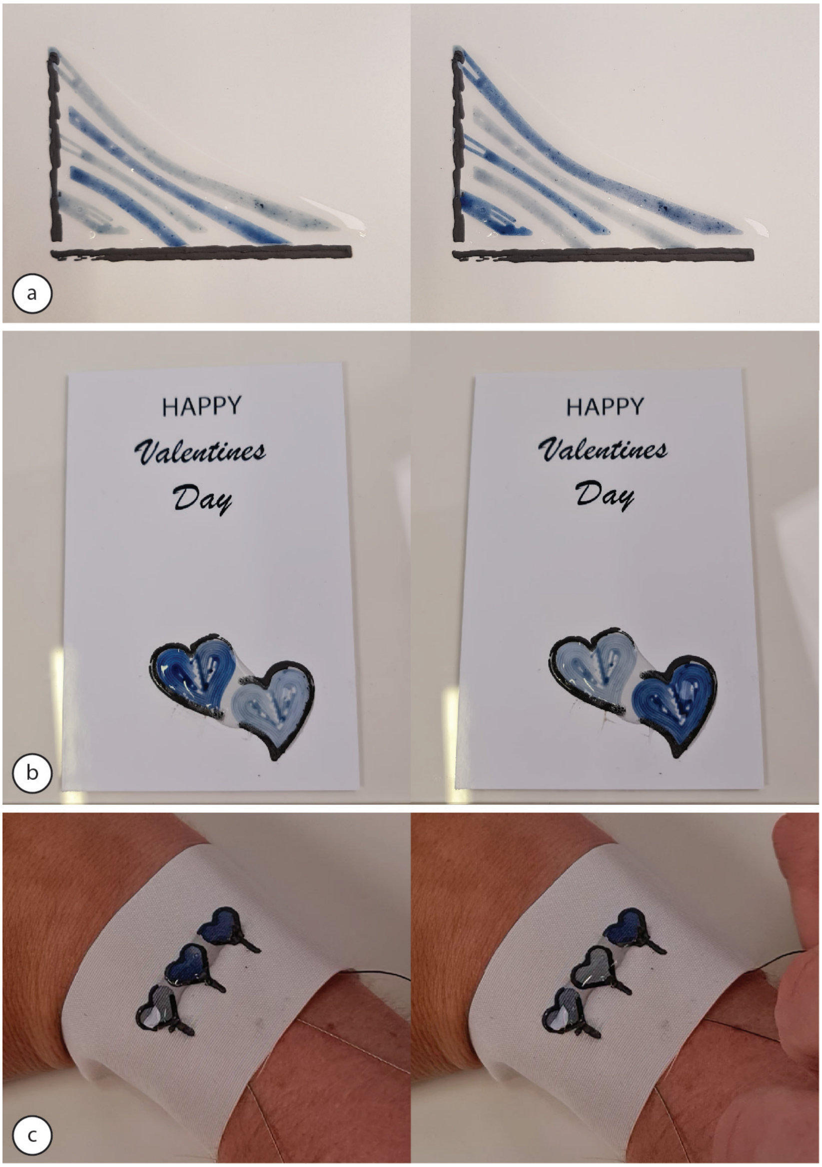

Fig. B.7: Functional prototypes printed using ECPlotter: (a) a display printed on ceramic tile, (b) a display printed directly on photo paper and (c) a display printed on polyester fabric.

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 be interactive where the design could change near instantly or over a longer period of time and act as a decorative element [39]. In our first example (Fig. B.7,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 [5, 40], 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. B.7,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 [41] or by creating a sandwich of fabric, display and fabric [42]. 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 [43, 44]. 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. B.7,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 now present possible next steps for improving the toolkit as well as the limitations.

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. B.7, 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 [38]. 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 [45]. 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 [20].

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.

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Part III

Papers - Application Scenarios

Paper C

Learning through Interactive Artifacts: Personal Fabrication using Electrochromic Displays to Remember Atari Women Programmers

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Abstract

In recent years makerspaces have gained traction as an environment where makers and tinkerers can freely create artefacts with digital fabrication tools. They are particularly suited for introducing new fabrication techniques because these spaces support hands-on experiences. Electrochromic displays are one such technology that has become possible to fabricate using new techniques and off-the-shelf tools which lends itself to be used in a workshop setting. Leveraging this development, we facilitated a makerspace workshop that introduced participants to this new technology. To limit the scope of the workshop outcome we used the little known history of female developers of video games (Atari) from the 1970's and 1980's as a design framing. The participants (undergraduates, 16 female, 2 male, aged 19 - 21 years) explored their role in development and through this exploration they created artifacts using novel electrochromic displays as designed responses. Their projects were displayed at a computer museum exhibition. Throughout the workshop participants answered daily questionnaires and kept records of their progress and the story of their chosen developer or game. Our analysis of the questionnaires and the resulting projects suggests that having a relatable and meaningful context increases both motivation and engagement of the participants. We discuss the extrinsic motivations that enhance engagement, and provide suggestions for introducing new technologies in the makerspace context.

1 Introduction

Making, learning, and makerspaces have been receiving attention in the HCI community over the last couple of years [1, 2], and have explored across different settings, domains, and in different parts of the world e.g. Asia [3, 4], America [5] and Europe [6]. Part of the reason why making has been celebrated is that making as a strategy allows for more inclusive access to technology, by lowering barriers to participation [7, 8]. However, research has demonstrated that makerspaces and the making culture can also exclude users from participation. In such spaces and in the maker communities in general, there is a lack of gender, ethnicity, and age diversity [9, 10]. Furthermore, the infrastructures available matter, for who has access to participate and engage with new technology [11]. And while there is initial research on makerspaces and inclusivity, recent research has reported a need for investigation into how new technologies fit into makerspaces, how they can be used for learning, and how teachers integrate Making into education [12–14]. While for most established fabrication techniques, such as laser cutting or 3D Printing, a large amount of tailored instructions are available, novel materials and fabrication processes are relatively less supported. One of these is Electrochromic display technology, a new kind of electronic display that has the potential to become part of makerspaces and learning environments, as it is relatively easy and inexpensive to make.

Electrochromic materials are a specially engineered class materials that change their visual characteristics in response to electric current. They have been around since the 1970's but it has only recently become possible to prototype and fabricate with them using off-the-shelf tools [15]. This type of material can be used to fabricate an *electrochromic display* (hereafter referred to as ECD), which enables the creation and

Fig. C.1: Participant fabricating electrochromic displays.

display of interactive printed graphics. These displays do not employ transmitted light, such as with liquid crystal, LED, or OLED displays, but rather, rely upon reflected light incident upon their surface, akin to e-ink displays. By applying a low, DC electric current, it is easy to switch between two graphic elements in the display, one of which is visible, while another is nearly invisible. Switching the polarity of the current changes which graphic is visible. It is possible to create an ECD with an ordinary, consumer-grade inkjet printer. But unlike graphic designs created on a computer and printed on ordinary paper, there are many steps of physical construction in designing and fabricating an ECD. These steps can be performed by non-experts (see Fig. C.1), but to do so requires not only learning how ECDs are constructed but also about their capabilities and limitations (e.g., speed of transition, vibrancy of graphics, balance of display). ECD composition and constraints require designers to think differently about their designs to ensure the display works optimally for any given application.

Because ECDs are transparent, flexible and require only a small amount of current to change state (<10 milliamps), they lend themselves well to designers for design prototyping, Internet of Things applications, and e-textiles [16–18]. They can be printed in arbitrary, irregular shapes and sizes making them integrateable into artifacts that require non-rectangular or flexible displays. Additionally, because advanced hardware is not required to drive them (in contrast to e.g., LCD and OLED displays), they are easily driven using simple electronic circuits or prototyping platforms such as Arduino. [19, 20].

In this paper, we present the results of a workshop that aimed to introduce participants who are new to makerspace facilities and novel fabrication techniques, while also exposing them to the little-known history of female game developers at Atari and their role in history, which served as a design framing. We introduced electrochromic materials as another resource in a makerspace, to explore not only the design and execution of a making workshop for learning, but also how new types of technology can be added to the makerspace. We chose the history of the Atari woman as a design framing because we wanted the participants to have a story to tell, to attract people that are usually not coming to makerspaces (in particular, women students) and motivate them to return. The artifacts that the participants developed where exhibited publicly at a museum after workshop.

Specifically, we are interested in these questions:

1. How do the limitations of the ECD technology influence the design activities in the makerspace?
2. How does the prospect of a public exhibition impact participants learning outcome?
3. How does using Atari Women as the design framing impact the participants' learning context?

Our findings suggest that the learning environment of the workshop should allow participants to explore the new technology in a thematic context that is meaningful to them. Moreover, their experience is more salient if the artifacts they produce live on beyond the workshop. Furthermore, we found that when introducing these novel fabrication techniques to novices, the availability of instructional materials and especially experts is highly important. Not only can they help by demonstrating the correct fabrication procedures but also support the participants to recover from mistakes through explanation and guidance.

The paper is structured as follows, first we present related work in constructionism and personal fabrication. We then present how the workshop was conducted and what the participants were instructed to do along with a description of our participants, data collection and analysis. Following this we present the results in two subsections, the first presents the resulting artifacts and their chosen story, the interactivity and the fabrication, and the second subsection presents the results from the data analysis. Finally, we present a discussion of our work and present three points facilitators should consider when introducing new technologies in makerspaces.

2 Related Work

We turn now to related work on Constructionism and personal fabrication that informed our approach.

2.1 Learning by Making

Build on Piaget's constructivist theory that a learner is contructing knowledge from prior experiences and through interacting with the environment, Papert proposed his theory of Constructionism, in which knowledge is constructed during the process of making artifacts that can be shown, examined, discussed, admired and probed. As a math teacher Papert wanted to engage his students in the same way art students were engaged in making and learning to make art. He used the programming language LOGO to let his students guide the actions and movements of a small robot "turtle" and saw it as a computational "object-to-think-with". For Papert the "turtle" functioned as a model for other objects, yet to be invented. From this work, constuctionist researchers found that LOGO enabled learners to understand abstract mathematical concepts in more accessible, concrete and relevant ways. Instead of receiving knowledge, the learners were making knowledge, with an emphasis on *making*, which is in contrast to instructionism, in which learners receive knowledge through didactic instruction [21, 22].

In 2016, Papavlasopoulou, et. al., presented a review of recent research on the Maker Movement and its role in formal and informal education [12]. Through search terms such as maker, making, makerspaces, movement, education, science education and a combination of the terms their meta-analysis found 2930 papers published between 2011 and 2015. They decreased this number to 43 usable studies by excluding irrelevant papers such as posters, non-peer reviewed and work-in-progress papers, and by using criteria proposed by Greenhalgh and Taylor [23]. Their review showed that the most common subject area for implementing Constructionism or "learning-by-making" is programming (32 of the papers reviewed had programming or programming in combination with another subject as the focus). Although most of the studies focused on programming, they still used tools such as basic electronics, Arduinos micro-controllers, and the visual programming language Scratch. They identified a need for further investigation into other tools for making, such as using digital and tangible materials [13, 14, 24]. Other tools used in the studies were 3D printing [25, 26], laser cutting and circuit board design [27], sewing and conductive materials [13, 28, 29], and MakeyMakey [30, 31]. Further, they found that few of the studies focused on gender issues or how making can benefit women.

2.2 Personal Fabrication

Personal fabrication is a growing area of research in HCI and was, in 2007, described by Neil Gerschenfeld [32] as *"the ability to design and produce your own products, in your own home, with a machine that combines consumer electronics with industrial tools."* The rise is evident in the amount of research in or using 3D printers [33–37], lasercutters [38–42], CNC machines [43–45] to mention a few. Later, Baudisch and Mueller [46], describe four elements that are required for a fabrication to transition from industry to the consumer: *(1) Hardware and material*, *(2) domain knowledge*, *(3) visual feedback* and *(4) machine-specific knowledge*. For a technology to become usable for personal fabrication the *hardware and materials* have to transition from the specialized equipment used in industry to one that can be used by a consumer. The expertise (*domain knowledge*) that industry professionals have should likewise transition into a form that is accessible to people with no expertise, for example, in the form of software. The software or system used should provide the *what-you-see-is-what-you get (visual feedback)* principle. Additionally, the software should reduce the need for a physical skill, similar to how Digital Video editing software removed the need to manually cut and align films when

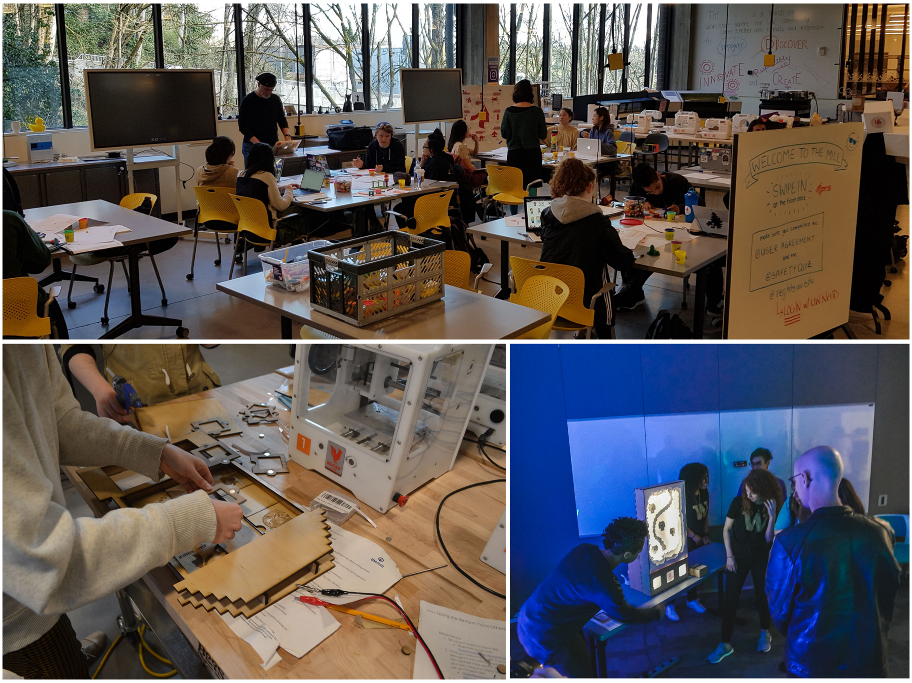

Fig. C.2: *Top*: Participants brainstorming ideas using Lego and Play-doh. *Left*: The *MixIt-Up* project group is making sure electrical connectivity is working. *Right*: The *Centipede* project is being presented by group at the museum exhibition.

editing films.

3 Method

We conducted a one week-long workshop (see Fig. C.2) as part of a credit-bearing university course called a Directed Research Group (DRG) which took as its theme the women who developed Atari games in the late 1970s and early 80s. The results of this workshop where exhibited at a well-known local museum of Computing. We told the participants that the workshop was a part of a research project, and a learning opportunity for them to work in the maker area. In addition, we also told them that our roles would be both as teachers and researchers during the workshop. As the exhibition was not mentioned in the description of the course, we told the participants on the first day of the workshop. The university makerspace had a variety of very common equipment available (i.e., lasercutters, 3D printers, CNC machines, embroidery machines, vinyl cutters, etc.) that are well documented and for which a large variety of learning materials can be found online. However, we also added novel and not-so-well documented ECD fabrication to the curricula as a mandatory element. This was done to investigate the students' engagement and learning with ECDs in a circumstance in which much of their exploration was done with minimal learning materials.

The main task for the participants was to create an artifact that celebrated the important contributions of women who developed Atari games in the 1970's. To design and construct the artifact, the participants used different fabrication tools in the makerspace. Students had to form small teams of three, and each group was supposed to focus on one Atari game and the woman who developed it to drive the design of their artifacts. As a result, the teams designed objects which captured and related to the story of the game and its creator. Participants first used low-fidelity prototyping methods such as sketching, clay modeling, or LEGO for idea generation and brainstorming. The ideas were then prototyped in cardboard before being digitally designed and fabricated in higher fidelity. As a means of conveying the stories, it was mandatory for them to also include ECDs into the designs. These had to be fabricated by the groups as well.

ECDs have some unique advantages and disadvantages. On the one hand, the displays are bendable, can be designed into all kinds of shapes (e.g., circles, triangles, irregular, etc.) and thus provide different affordances compared to regular display screens. For this course, we only opted for the most basic construction method of an ECD, the vertical stack [15]. This means that the displays only can contain two different graphics, showing only one at a time. Once a display has been fabricated, its graphics designs cannot be changed, which posed additional design challenges for participants.

All these elements - and especially the choice of ECDs - were selected because they follow the "low floor - high ceiling" approach, meaning that getting successful and engaging results is relatively easy but the technologies have a large potential for exploration and extension. Furthermore, the chosen topic has creative, playful, and engaging elements – "wide walls" - that allows for easy personalization and expression for every group. These approaches are in line with Papert's vision of Constructionism.

Additionally, to highlight the histories of the Atari women engineers to a broader audience, the artifacts that students had created were presented in an exhibition at a well-known computer museum, two months after the workshop. While this workshop was part of a university course which would give the participants credits, we were interested in how the exhibition would impact the designs and learning outcomes.

3.1 Workshop Structure

We ran the workshop sessions from 9AM - 5PM, Monday to Friday, starting each day with a short introduction explaining the goal of the day. Brief expository lectures introduced participants to the workshop while still giving them enough time to generate ideas and fabricate. We instructed participants on the design context of the workshop (Atari women programmers), introduced the makerspace tools and equipment available (e.g. laser cutters, 3D printers) and how to design and fabricate ECDs on the first day (Monday). Instructions were kept short to afford more time for participants to learn-by-making [21]. The participants also formed groups, discussed which woman or story to work with, and each participant fabricated their own ECD. This helped them to better understand the affordances and constraints of the display technology during design ideation. We instructed the students on sketching and modeling on day two, after which each group brainstormed, sketched, and modelled three ideas. These were presented to the rest of the participants and teachers for feedback. By midday, each group had selected one idea and started prototyping their artifact using the tools available in the makerspace. The participants had free rein to work on their artifacts on days three and four. Close support was provided on an individual- or group-basis. This allowed each student or group to follow their own tempo and receive information when needed. We encouraged groups to take videos and photos, and to write down findings from their own research during the workshop. We asked participants to create a short 2- to 4-minute video of their project, which was shown during a theater session on Friday afternoon. Students continued to refine their projects after the workshop, in preparation for the museum exhibition.

3.2 Post meeting and Exhibition

We held a followup meeting a month after the workshop, to ensure each group was ready and had all the required material for exhibiting their artifact. During the meeting each group presented their progress and a list of things they needed help with to ensure they were ready for the exhibition. Additionally, the meeting was used to inform how the exhibition would progress, who would likely attend, and what each group needed to prepare for the exhibition.

3.3 Participants

18 (2 male, 16 female, age 19 - 21) undergraduate engineering students were recruited for the workshop. For this, a description of the workshop including short descriptions of the ECD technology and the Atari women framing was advertised on the university website. Interested students could sign up by writing a short motivational letter that included their backgrounds, their technological experience, their knowledge of gaming and Atari, and their expectations of the workshop. The 18 participants were selected by the workshop facilitators based on these letters. All participants had taken introductory courses in programming and eight students had taken courses in human-centered design, interactive systems design and technology, or both. No participant had prior experience with makerspaces and their tools, nor with ECDs.

3.4 Data Collection

The participants answered a pre-workshop questionnaire, and completed daily reflections during the workshop in the form of questionnaires with open ended questions such as "*What was difficult / easy when you where identifying a focus for your design?*", "*Describe an important 'a-ha' moment from today. An 'a-ha' moment is a situation where you learned something, solved a problem, found a way to go etc (please write 5-10 sentences)*" and "*What was the most challenging aspect with building your artefact today? Challenges with technology, machines, materials etc*". Each group was asked to keep records in form of a notebook throughout the week capturing their progress, information gathering, and the story of their artifacts. Participants documented their work with photos and

Structured Learning	Relatable Context	Extrinsic Motivation
Fixed expectations	Meaningful context	Being able to show off work
Ideation and Prototping	Overcoming difficulties	Make a complete project
Novel technology	Approachable people	Having a goal
Learning new things	Collaborative	Different skillsets
Experience is rewarding	Meeting likeminded people	Interesting technology
Workshop was fun / cool	Free expression - Freedom	Experiencing firsts
Working in small groups		
Hands-on experienceing		
Teaching others		

Table C.1: Initial categories identified in questionnaires, listed by the themes they were sorted into.

video throughout the workshop and the exhibition. We obtained permission from participants to use their images and photos for dissemination.

3.5 Data analysis

We used a two-step, grounded theory approach to analyze and code the questionnaires [47]. In our initial coding we identified sentences or words that relate to learning about new technologies and tools, curiosity and engagement, and collaborative explorations. We identified 22 categories (see Table C.1) that were sorted, compared and filtered to three salient themes (*structured learning*, *relatable context*, and *extrinsic motivation*) which will be described further in the fabrication environment section. We analyzed each participant's self-record of their progress and photographs taken during the workshop to understand how the use of ECDs affected the project designs.

4 Results

4.1 Artifacts

To answer the first research question, we present the final artifacts that the students exhibited at the museum, and analyze them with respect to how the *story* that the students wanted to tell informed their design and use of ECDs, how *interactivity* was implemented and used with the displays, and finally how ECDs factored into the *fabrication* of the artifacts below.

Story

Each team built a project using a game or the story of Atari women programmers in gaming as its design framing. Some project artifacts combined both. A key part of the design work was for participants to identify what to incorporate into their design as well as whether their project focused on the subject of the game or of the Atari

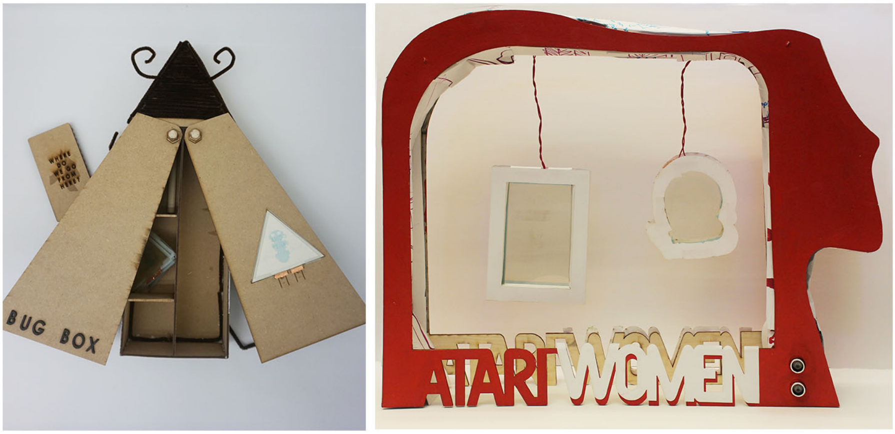

Fig. C.3: *Left*: LadyBug artifact with wings slightly open and one display placed on the wing. *Right*: Suki Lee artifact with both ECDs powered so the graphics are not visible.

women programmers. As noted above, a selection of these narratives was presented to participants during the workshop introduction. Interestingly, no group focused on the same context or game. A brief summary of their projects provides a glimpse into the kinds of artifacts the teams created.

The *SukiLee* artifact comprised an approximately 50cm by 60cm picture frame designed in the shape of the workshop's "Atari Women" logo (see Fig. C.3, right). In the large frame two smaller frames, a square and a irregular shape, are attached. The two smaller frames contain ECDs. Suki Lee was the first Chinese-American programmer to work for Atari, yet her stories are hardly known by anyone. The participants wanted to emphasize Suki Lee's contribution of *Donald Duck's Speedboat* game for the Atari 2600 gaming platform. This game was only released in Brazil and never internationally. Further, the game was only published in a small batch and thus is very rare. Because the game was only released in Brazil it was largely "invisible" to the wider public. The participants developed an ECD with the silhouette of Suki Lee's face and one with the cover graphics of the *Donald Duck's Speedboat* game. The displays can shift from portraying a visible image to hiding the image, depending on a shift in electric polarity, triggered by a distance sensor. The participants developed the artifact so that the graphics are invisible until viewers approach the frame within 30 inches. This artifact focuses on Suki Lee and her circumstances surrounding the development of the *Donald Duck's Speedboat*. The participants leveraged the ECD's ability to make graphics appear and disappear as a feature of the design, thereby manifesting Suki Lee's story.

The *BugBox* artifact is designed as an interactive moth. Spreading its wings opens the box (see Fig. C.3, left). Inside the box are several triangular-shaped ECDs. Their design is a nod to the computer scientist Grace Hopper, who found the first bug (a moth) in a computer system. The participants designed and fabricated 13 ECD pieces, each bearing the name of a female Atari programmer. Each of the display pieces can be

Fig. C.4: *Left*: The *Spider-Man* artifact features a building facade with multiple ECDs and two movable, 3D-printed characters. *Right*: The *Centipede* artifact is the physical representation of the 2D game with mushroom-shaped electrochromic displays taking the form of shootable objects. A lasercut controller selects which character is actived.

activated by placing them on electrical contacts situated upon the moth's wings. The shape of each display piece piece echoed the shape of a moth, leveraging the capability of ECDs be created in irregular shapes, thus creating a coherent design.

The *Spider-Man* artifact comprises a physical representation of the original digital user interface of the *Spider-Man* game and thus is designed as a building facade, on which Spider-Man is jumping around. On the facade there is one door and 12 windows; each window containing either a hand-drawn graphic or an ECD (see Fig.C.4, left). The participants modelled and 3D-printed two characters (Spider-Man and Spider-Gwen), inspired by the *Spider-Man: Into the Spider-Verse* movie. Magnets embedded in the building facade allow the two characters to "jump" around the house, activating the ECDs. Each display is designed with a logo from a game developed by Atari women and text that shifts between the name of the game and the name of the developer.

This artifact incorporates the stories of four different women who developed games, namely Laura Nicolich (*Spider-Man*), Patricia Goodson (music in *Pac-Man Jr.*), Betty Ryan Tylko (*Pole Position*) and Noelie Alito (*Moon Patrol*) while drawing inspiration from the *Spider-Man* game in its physical appearance and interaction. By designing and fabricating an ECD for each of the Atari programmers, participants engaged with multiple histroical narratives, incorporating them into their Spider-Man centric design.

Fig. C.5: *Left*: The *AlitoLamp* artifact with illuminated lamp and a 3D-printed joystick. *Right*: The *MixIt-Up* artifact used multiple ECD pieces to create a "remixing" exploration of characters.

Similar to the *BugBox*, the participants leveraged the ability to fabricate ECDs in any shape or form, thereby enabling them to integrate the display neatly into the windows of the building.

The *MixIt-Up* artifact is a laser cut puzzle game allowing a player to create various characters, all based on the original characters in Dawn Epstein's *Strawberry Shortcake* game (see Fig. C.5, right). Following the "easter egg" concept from gaming culture, which became a way for developers to embed "secret" surprises into games (often displaying their own names), *MixIt-Up* also has an easter egg, thus incorporating a multi-layered story into the artifact. The *Strawberry Shortcake* video game was created at the same time as *Care Bears*, both by Parker Brothers, who employed two women game developers, Laura Nikolich and Dawn Epstein. These two games both targeted girls, however Parker Brothers decided not to release *Care Bears*, since they believed that too few girls played games to make it financially viable. To create the ability for players to mix-and-match characters, this team laser cut multiple pieces of wood which, when sandwiched together, would create physical depth and increased sturdiness in the game pieces. Six pieces of the puzzle were fabricated containing four different characters. One of the characters was the ""easter egg". As with the *Spider-Man* artifact, this game linked both the developer's historical narrative and gameplay. The interactivity echos the gameplay of the *Strawberry Shortcake* video game in physical form. At the same time, the ECDs were designed to be replicas of the characters in the game. As with both the *BugBox* and *Spider-Man* projects the project teams utilized the ability to fabricate easily-powered ECDs in custom shapes, taking advantage of the fact that the displays are very thin and are easily integrated with other materials (in this case, laser cut wood).

The *AlitoLamp* project is an interactive lamp which incorporates a 3D-printed joystick (see Fig.C.5, left). The participants honored the work of Noellie Alito who, together with Mark Acherman, developed the Moon Patrol game released in 1982. Moon Patrol is a side-scrolling game in which the player controls a moon buggy while avoiding obstacles on the moon's surface. The project comprises a five-sided lamp and a 3D-printed joystick mounted on a box. Windows on the five sides support lunar landscapes as normal printed graphics and transparent ECDs through which the landscapes are visible. This creates the illusion that the rover is appearing and disappearing on the lunar landscape as it traverses around the lamp, imitating the side-scrolling format of *Moon Patrol*. In contrast to the other artifacts, the AlitoLamp only focused on the game. Similar to the *SukiLee* artifact, the *AlitoLamp* uses the affordance of appearing and disappearing, creating the illusion of interactive printed graphics. Where the *SukiLee* artifact related the invisibility of women the *AlitoLamp* artifact combined the displays with ordinary printed graphics to create "interactive" printed graphics.

The *Centipede* project is an interactive light box that contains both digital technology and paper crafting materials. The artifact was developed as a physical representation of the game Centipede, created by Donna Bailey. Donna Bailey worked at Atari's coin-op department where she experienced an unwelcoming, male-dominated work environment. The team incorporated cut paper elements to create an illusion of depth and parallax, as is seen in platform games (see Fig.C.4, right). They fabricated seven ECDs, four of them being mushrooms from the game and three of them being the player's character at different locations. The mushroom displays contained phrases or words (i.e., "Boys Club", "Lazer", "Wage Gap" and "Narrow Minded") symbolizing the bad experiences Donna Bailey experienced during her time at Atari. The three bottom displays were created to symbolize a character that can have three positions. These displays were placed adjacent to each other in a wooden frame located at the bottom of the artifact, whereas the mushrooms were scattered in the central window area around the centipede cutout. A smaller box with three buttons attached to the main enclosure functions as a game controller, incorporating buttons that move the character left and right and allow it to shoot at the mushrooms. Similar to *AlitoLamp*,*Centipede* focuses solely on the video game as an inspiration for its physical appearance and interactivity, but adds context in the form of the phrases associated with each of the mushrooms. Similar to the *SukiLee* artifact, the *Centipede* artifact leverages the ability to create ECDs in irregular shapes; the mushroom displays were fabricated and cut out in the shape of a mushroom.

Interactivity

The interactivity of each of the artifacts was linked to the electrochromic displays. ECD display technology's switching capability lends itself to being used for interactivity and each artifact did incorporate this feature.

The *BugBox* artifact required the user to manually place the ECDs onto the artifact to activate them. This created a tangible interaction, through pressure applied by the fingers to ensure a conductive connection between the artifact and the displays. One wing of the artifact had a battery holder attached to its underside, with two wires going through the wing to two pieces of conductive tape. The conductive tape affixed on the wing allows a player to randomly select and orient the displays and see the different graphics printed in the displays. This is a simple, yet effective use of the fact that ECDs need very low power to actuate, in contrast to the advanced electronics other display technologies require. Thus, simple physical interactions can be easily designed.

In contrast to *BugBox*, which derives its interaction from physically placing ECD displays onto metal contacts, the *AlitoLamp* incorporates a push-button. The button initiates an activation sequence that imitates the moving moon buggy. The push-button and each of six displays in the lamp assembly of the artifact were connected to an Arduino micro-controller, which allowed the team to program how the displays were switched, upon receiving an input from the button. The Arduino software sequentially shows only one display at a time, thereby creating a simple animation that gives the illusion of a moon buggy driving around the lamp. This artifact utilizes the ease of driving multiple ECDs with off-the-shelf prototyping platforms.

The *SukiLee* artifact incorporated a distance sensor to switch visibility of the displays, which was the locus of interactivity in the artifact. By connecting the two displays and a distance sensor to a micro-controller, the group was able to use proximity for interaction. The silhouette of Suki Lee and the graphics from the *Donald Duck's Speedboat* appear when viewers move close enough to it. The *MixIt-Up* artifact uses a similar technique to activate the displays as *BugBox*, but still managed to so in a more complex manner. The group laser cut smaller frames for their character pieces, and their design included mounting points for small magnets. This allowed them to integrate the ECD into the frames of the character pieces and, cleverly to use the magnets to conduct electricity, triggering the interaction. Two metal conductors were connected to a battery pack so that when the character pieces are correctly placed onto the frame, electricity will be conducted from the bars through the magnets into the ECD displays. The designs for their character pieces consisted of silhouettes of each character's lower, middle, and top part. Each display contained pieces comprising two complete characters and each character would be fully visible only if all game pieces were oriented correctly. Incorporating multiple characters into their design enabled the team to create an interaction that enables the user to do exploration and remixing of the characters, until they find and orient all the pieces for one full character. Although this artifact did not use any advanced electronics or programming, the students still managed to create an ingenious, interactive solution that utilizes the unique capabilities of ECDs.

The *Spider-Man* artifact resembled the front of a building with multiple windows that either had static illustrations or ECDs, and two 3D-printed characters that magnetically attach to the frame (see Fig. C.4, left). This allows a user to move the characters around on the enclosure and thereby actuate the various displays. By attaching hall effect sensors to the building facade and connecting them and the ECDs to an Arduino, the project team was able to use the 3D-printed characters as interactive objects that switch the displays.

The *Centipede* project team developed a physical representation of an arcade game, using ECDs to indicating where a character is positioned. The user moves this by pressing left or right buttons. Additionally, the team added a "shoot" button which would activate one of the mushrooms in the center part of their artifact (see Fig. C.4, right). The Centipede project the most complex interactions of all the artifacts, however, most of that complexity comes from the software design and the fact that ECDs can easily be driven and switched by an Arduino.

As described, both *story* and *interactivity* factored heavily into the design of the

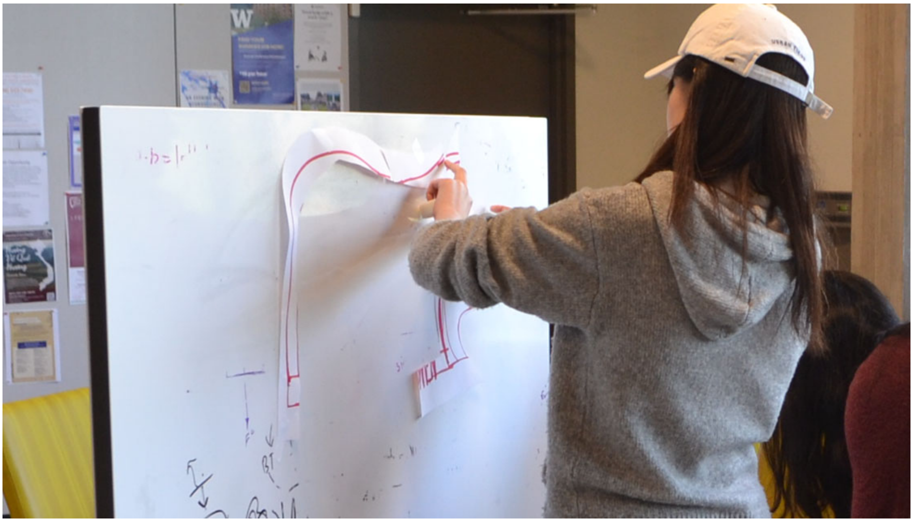

Fig. C.6: Participants brainstorming dimensions and shape for the SukiLee artifact.

objects, and shaped both the process and the final outcome. In the next section, we describe how the tools present in a makerspace the ECD technology shaped the fabrication.

Fabrication

In our analysis of how the participants used the equipment available in the makerspace to construct the appearance, functionality and shape of their projects (and in particular, considering the ECDs), we found that groups used a variety of strategies for the way they engaged with the tools, how they found new information, and fabricated their projects. While the makerspace contained a wide range of equipment (laser cutter, 3D printer, CNC machines, embroidery machines, vinyl cutters and more) freely available to the participants, all participants used on laser cutting and only two groups used 3D printing. We noticed that the laser cutter became the go-to equipment due to its ease of use and fast learning curve. This might be explained by its ease-of-use but the ready availability of operating instructions on the internet was also a factor. Although all the projects used laser cutting, the manner in which which ECDs factored into each design differed.

The *SukiLee* artifact comprised two pieces of laser cut wood which together created a sturdy frame and the perception of depth. Because the ECDs were hanging from the frame on a wire, the participants did not need to create precise measurements. This meant that they could easily design and laser cut the frame without getting hung up on precision (see Fig.C.6). This gave the group some freedom, without necessitating multiple prototype iterations and helped them to design rapidly.

The *BugBox* artifact's design similarly did not require a great deal of precision to design its physical appearance, because as most of their laser cuts were simple shapes. Although the project's appearance was simple, the team still had to precisely align holes in the moth's wings with metal rods to create a pivoting action. The team engraved one of the wings to contain a outline of the ECDs, and the silhouette of two fingers indicated where the user should places the ECD displays to activate them. They also did not need to carefully take the displays' technicalities into consideration for laser cutting the shape of the box, a they were loosely stored inside it. However, for their engraving they needed to ensure size and shape was the same as the displays they created for the artifact.

The shape of *Spider-Man* is based on a simple construction. The artifact uses finger joints to connect the sides of the box to other sides. This required the group to independently research how to design such joints and instead of manually designing the joints, they used online tools to create them. As the project used several ECDs, the participants had to take into account their sizes and shapes during the design phase. Also, because ECD displays are transparent and do not have their own source of illumination, the team had to consider how to ensure the user could see the prints them clearly. Additionally, the project contained two 3D-printed characters, which the group modelled and printed themselves.

Similarly, the *AlitoLamp* artifact used finger joints to connect the pieces (but for the lamp itself), the project team used a non-rectangular shape, which required them to research how to ensure the joints would properly connect. Because they had to stack inkjet-printed graphics with ECDs to give the illusion of a moon buggy traversing the moon, they had to consider how this stacking affected the look of ECDs and the size requirements for the lamp panels. This artifact also used 3D printing, however, in contrast with the *Spider-Man* artifact, this group found a model of a joystick online and modified it to their needs before 3D printing it.

The puzzle interaction of the *MixIt-Up* project required laser cutting several pieces that would fit together without getting stuck, in contrast to other teams' finger-jointed designs. In this design, the team had to take into account how to integrate the displays into their puzzle pieces. They did this by creating the frame of each pieces in just the right size to integrate the display, while still providing sufficient room to attach the magnets. The group also had to take into account that the user should be able to pickup the pieces while being able to place them in two orientations and on two sides. To create this, they needed to ensure that the magnets could be embedded into the frames while taking care that the frame could still support the placement and removal of the puzzle pieces. Additionally, their design used multiple layers of laser cut wood to create the depth required for the interaction. The design was visually enhnaced with decorative engraving.

The *Centipede* artifact is the only one that uses a combination of paper crafts, laser cutting, and irregular shapes for the ECDs. The enclosure of the artifact itself is designed using finger jointed connections. Carefully cut craft paper pieces are layered together to create the illusion of depth. The team designed and cut the paper with the ECDs in mind, wanting to create displays with a mushroom shape to symbolize the shootable items. To give the impression of a movable character, the team arranged three ECD displays in the enclosure surface. Although they did not need to create high precision cutouts for these character displays, the team still leveraged the ability to create displays with irregular shapes in their overall design.

4.2 Learning Context

To answer our first two research questions we look to the learning context. The fabrication workshop took place in an environment comprising both the structural learning activities as well as the situated context created by the link to the Atari women.

Structured Learning

The structure of the five-day workshop was designed as project-oriented and student-guided, in accordance to Papert's constructionism. While each day had a theme and an objective, the way in which the participants chose to engage with the theme and reach the objective were flexible. That did not mean that we took a laissez-faire approach but that we followed the participants ideas and curiosity and supported them through supervision of design, concept, tools, technologies and fabrication aligned with the participants needs and interests at certain times in the project. It was entirely up to the participants how they spend their time, as long as they were working towards the objective of the day. Other required information (e.g. information on how to use the laser cutter, its safety instructions, and digital design requirements) was provided as needed. This approach allowed the participants to have information fresh in mind when working with the equipment. After these short ad hoc introductions, the groups used the equipment and asked for additional support if needed. Having this freedom to work as they saw fit and use the machines as they needed produced an engaged and self-driven environment which the participants particularly valued:

> "*I did not expect as much freedom as we had with our group, which I really think was helpful for our design critique and creativity.*" (Participant #8)

> "*I think I learned a lot more from having the flexible schedules and design freedom.*" (Participant #11)

While this teaching approach required much more from the us, the teachers, in adapting all interaction to individual groups, it also produced a very engaged and self-motivated learning situation that was important for the participants' learning process. The semi-structured and flexible workshop allowed the participants to engage their agency and self-guided learning. For example, participants were asked to identify three ideas for stories about Atari women and collect additional data about their ideas on the first day of the workshop. The purpose was for them to argue their design choices by forcing them to ground their decisions in data, while still keeping the process open.

Although we requested that the design teams come up with three ideas, it was up to groups to select, based on their data, which idea had to be prototyped. Also, we did not restrict the participants to particular equipment or materials except for the requirement to use ECDs. Making the participants use the equipment themselves, with minimal guidance, resulted in a lot of learning by failing, which they found positive as can be seen in the following quote:

> "*What surprised me the most was the structure of the DRG [i.e., the workshop]. In general, the structure of the DRG was much more self-guided (group-guided?) than what I would have anticipated. The hands-off approach allowed for more mistakes and more creative freedom, which I enjoyed.*" (Participant #13)

A core part of the workshop was for the participants to use ECDs, which in personal fabrication is a novel process; not much learning material can be found on the internet. Nevertheless, each group learned to design and fabricate ECD displays with a variety teaching materials (e.g., written instructions, power-point presentation, live-demo, and instructional videos). Because the students did the fabrication themselves, they encountered the technical challenges that would then in turn inform their designs for their projects. This openness to use the makerspace equipment as they saw fit after their first introduction and the goal of creating a fully-functional project was also found very positive as can be seen in the following quote:

> "*I experienced a lot of 'firsts' for example, first time using laser cut, first time making the ECD displays, first time attending DRG and learned a lots from everyone. I learned from ideation to prototype and to the actual project, every single stage need a lots ideas and work. I am so appreciative that I can have this wonderful experience.*" (Participant #6)

Relatable Context

We found that because the participants could relate to the context of hidden women in tech and had to create an artifact that brought to light those women encouraged and motivated them to do more. Analyzing the qualitative data from the questionnaires we found that that the meaningful and relatable context, which we refer to as *situated learning context*, was crucial for the experiences of the participants.

The majority of the participants (16 of 18) were women and many themselves they could relate to the idea that we are looking at the hidden life of women. Further, they were also interested in Engineering and games. They used those interests and personal experiences as part of their design process. For example, the participants who created *Centipede* embedded their own experiences of micro-aggressions into their project and therefore had experienced similar stigmas as those of for example, Dona Bailey, who was represented in the *Centipede* artifact. By making the context of the workshop relatable, participants were motivated to push the limits and give their best as the below quote illustrates: As a majority of the participants were women themselves and worked with or wanted to work in Engineering they had at some point in their lives experienced similar stigmas as those of the hidden women that were the context of the workshop. This relatability motivated several of the participants to not only do more but also research beyond the given material provided by the instructors.

> "*It made me motivated knowing we were working about the Atari Women but I think it is because I, myself, think of me as a strong woman and knowing that I could bring to light other strong women pushed me to do a little more than if it was going to be men.*" (Participant #8)

The meaningful context — allowing participants to explore the Atari women and researching additional material — shaped the workshop dramatically. The role models the Atari woman presented, whom the female participants could relate to, served as a motivational factor as well as a basis for the content of the artifacts. Several groups chose to initiatie independent research into the games made by women in terms of gameplay, design, and interaction features. A few groups that chose to research further did so to find details about the games the women had developed that were not previously known to us. For example, the the *MixIt-Up* team uncovered new information about gameplay and graphics of the *Strawberry Shortcake* game developed by Dawn Epstein.

This then informed them about how they meaningfully could utilize ECDs in their artifact. By providing relatable context and content, the participants were driven to figure out how to combine it with the technology as illustrated by the following remark.

> "*When we were told to combine the stories of the Atari women with the technology, I thought it would be an interesting design challenge. I was motivated to figure out how to tell someone's story without words and through their own accomplishments.*" (Participant #11)

The relatable learning context encouraged the participants to engage in a deeper understanding of the affordances and constraints of the ECDs. This in turn allowed them to successfully design and fabricate functioning artifacts that each told a story about the hidden women developing games in the 1970s.

Extrinsic Motivation

Giving the participants the goal of exhibiting and presenting their artifact at a later time outside of family, friends and university (*extrinsic motivation*) excited them to push further and increase their engagement. This is, for example, seen in multiple groups painting their artifacts to give them a more finished look. And the teachers experienced multiple days where groups wanted to stay later than the planned time of the workshop to have enough time to reach their goal. Also having to exhibit an artifact with subject of meaning to the participants was very positive to the participants as seen in the following quote:

> "*I had no idea what our main goal was going to be with this research group, but when I found out that we were going to present artifacts that we made for women, I was more than ecstatic.*" (Participant #8)

Another consequence of having a goal beyond the workshop was that several participants expressed they wanted to continue working on their artifacts after the workshop ended. Their motivation was such that specifically requested out-of-hours access to the makerspace to continue their work. Here we observed, that the students did not only work towards getting their credit points, but actually developed intrinsic motivation and reflecting on what could be improved to ensure they had the optimal artifact for presentation as seen in below:

> ""*I am certainly planning to continue working on it. I showed some pictures to friends and family, who were very receptive and interested. I want to finish mounting the display and lock the wiring in place to hopefully reduce issues later on. I could also see updating code to make it more intuitive to use and see screen changes on. I want our project to look as good as possible for its final presentation.*" (Participant #2)"

5 Discussion

We now turn to a discussion of the results of our work, and provide suggestions for introducing new technologies to the makerspace repertoire. Our findings suggest guidelines that fall into three main categories:

- Participant motivation
- Design framing and relatability
- Support to explore and fail, especially with novel technologies

With respect to our first research question, *"How does a public exhibition impact participants' learning outcomes?"* it became quite clear that having the artifacts live beyond the workshop and having to present them at a museum to people other than friends, family and people at the university had a significant impact on the learning outcome. It served as *extrinsic motivation* and was essential for the workshop participants, as it created a meaningful context for their engagement and encouraged them to produce detailed and well-developed artifacts.

The *extrinsic motivation* was shaped by the planning of an external event, the exhibition at the museum. The students cared how their projects would be read by the general public and wanted to ensure that the stories of the Atari women were understood. While an exhibition could also lead to a certain level of pressure which might counteract the participants' motivation, we did not find any evidence for this here. It is of course, not always possible or feasible to stage an exhibition of work, and it might also not be practical for all maker workshops. However, we recommend that facilitators of such workshops ensure that its work products can be easily shared with others outside of the makerspace, for example through pictures and videos, or social media as suggested in [48], at a minimum. While sharing in itself is not novel to constructionism, our findings validate that it is also important for early University students and that having to share the work outside of the makerspace further adds to the motivation of the participants.

Moreover, because the participants could relate to the historical figures, and felt these histories were of personal importance to them, they devoted extra effort to creating artifacts that would do justice to those women. This contributed to our second question, *"How does using Atari Women as the design framing impact that participants' learning context?"*. Giving participants relatable stories and role models substantially increased their personal motivation. This is in accord with the findings of Mellis et. al., who showed that individual goals and scope are important for personal fabrication [49], and also the work of Aronson and Laughter [50].

This increase in motivation was also evidenced by the fact that most groups initiated their own research and sought both contextual/historical and technical information not provided by the workshop facilitators. We set the stage, but they drove their own inquiries, and we allowed them the space and time to conduct their research. For our approach to be adopted elsewhere, facilitators should ensure that their teaching materials and learning environment will support participants finding more information independently, and ensure time for this. We did this by a incorporating dedicated design session into the workshop in which participants ideated several concepts, gradually narrowing down to the core ideas they wished to communicate with their projects. This was further supported by the latitude to freely use the variety of different resources, technologies (in our case, ECDs), fabrication tools, and other equipment available in makerspaces.

Again, we acknowledge that it might not always possible to find a suitable learning context, with relatable role models such as the Atari women. However, prior work has shown that when facilitating such workshops, not only are the individual learners' *goals* important for the learning outcome, but also that *imagination and fantasies* (evoking images of objects or situations not present) represent a key ingredient of effective (and fun) learning [51, 52]. Besides using actual historical events as design framing, we suggest that another strategy might be to repurpose relatable fictional stories.

Our third research question focused on the specific characteristics of the novel display technology we used in the workshop: *"How does the limitations of the ECD technology influence the design activities in the makerspace?"*. We found several elements that highlight the challenges and opportunities of ECDs.

One of the unique features of ECDs is that they can be fabricated in irregular, arbitrary shapes, using ink-jet-printed graphics. This means that our participants could create relatively complex graphics controlled by simple technology (i.e., a simple 1.5 volt AA battery or basic micro-controller, such as Arduino). Other low-voltage displays require much more complex display driving circuitry. All participant groups exploited this by creating detailed graphics embedded into their projects, which meant they each had a fairly detailed user interface which worked, even though the participants did not have a lot of programming experience. Apart from this, we also noticed that using ECDs resulted in projects that were not confined to the common understanding that display screens are rectangular. Several artifacts used displays that were not uniform, such as the *BugBox* project's triangular displays and the *Centipede* artifact's mushroom shaped displays.

Perhaps the most remarkable outcome leveraged another unique feature of ECDs: the printed graphics can be made invisible. A few of the projects used this to accentuate the story surrounding the Atari game developers, or the game itself. This is especially seen in the *SukiLee* project, in which the participants used invisibility to demonstrate how these women programmers were *historically and culturally invisible*. Their work leveraged the novel technology to articulate and accentuate one of the key aspects of the historical narrative of the women Atari developers: to most people, they did not exist. This interpretation was a powerful expression of the group's understanding of both the historical context of the workshop's design framing and the capabilities of the ECD technology.

We observed that the constraint of not being able to change the graphics after fabrication meant that the groups had to thoroughly think through their design. Design constraints often lead to novel workarounds. This further meant that what participants focused on had a big impact. The inherent technical limitations of the displays (e.g., cycle time, vibrancy of graphics) limited what it is possible to present in the displays. This required the groups to sharpen their analysis and overall story of the artifact.

We believe ECDs show promise for experimentation and novelty in participatory workshops because they are easy to fabricate but at the same time have a large potential for expression (low floor - high ceiling). However there are certain elements for improvement. Previous work reports that ECD technology is robust [15] which holds true when fabricated and used correctly. Nevertheless, unexperienced makers can fall into several pitfalls that might not be immediately self-explanatory to them. Several groups experienced burnt displays due to either not UV curing them properly or powering them with a too high voltage for prolonged periods of time. Compared to a laser cutting process, where burn marks can be easily explained by either using to much power or too low speed this does not extend to ECD technology. The interplay of electronics and the chemical process in ECDs make them hard to understand compared to other maker technologies. Here specific electronics driver board for the displays that contains logic for driving displays without damaging them could be used. However, this would also limit what the participants are able to explore with the electronics and therefore also their exploration options during the workshop.

While mistakes can be an efficient and memorable experience for learning, it is only valuable if explainable, which is not necessarily a given with ECDs. The right amount of support is critical. We found that it is important to provide participants possibilities to explore and fail. Too much guidance hinders one of the most positive characteristics reported by participants, that is, the latitude to creatively address problems. It is also important to develop teaching resources tailored to the sweet spot that provides "just enough" learner support. Effective teaching materials should also communicate potential failures, explaining not just what to do, but also "what not to do", with examples of fabrication errors and the failures that result. As [12] report, there is more work to be done on how to make effective maker instruction material. Another pitfall of ECDs is that designing displays with optimal switching capabilities requires balancing the amount of ink on both sides of the displays. Optimal designs should have balanced areas of electrochromic ink that are activated or deactivated. Our participants had to do this by either guessing or fabricating and hoping they had a balanced amount. Simple software tools that can indicate whether or not the graphics for the two sides are balanced in ink amount. This improves robustness and lifespan.

This work contributes in several ways to future designs of makerspace driven workshops. Having a guiding theme, that the participants can relate to drastically increased their engagement. The extrinisic motivation of the exhibition sparked further motivation as well. We demonstrated that novel technologies (ECDs) can be easily integrated into the process as well, but also laid out several pitfalls that might arise from this. While we specifically focused on ECDs, the findings with regard to learning can also be applied to other novel fabrication techniques. To summarize into points lecturers and facilitators should consider when facilitating workshops with new technologies:

- *Relatable Guiding Theme*: Facilitators should provide relatable role models where participants are tasked with researching their background and history to find relevant information for the workshop outcome. Where this is not possible we propose repurposing relatable fictional stories that participants can identify with.
- *Extrinsic Motivation*: Arrange an event where participants have to share their work outside the makerspace. We used an exhibition to great success but where this is not feasible we recommend makerspace facilitators set up other forms of extrinsic sharing, e.g. in the form of social media stories or videos.
- *Introducing Novel Technologies*: Bringing new technologies into the makerspace

should allow exploration and failing while teaching materials provide both what to do and what not to do. The materials should also provide examples of errors and what caused them so it can be backtracked to where in the process something went wrong, similar to e.g. how the 3D slicer software Simplify3D provides a print quality troubleshooting quide. [1]

6 Conclusion

We presented the results of our exploration into how creating an interactive artifact in a fabrication workshop can teach participants to work with a new technology, in this case ECDs. We ran a week-long workshop with a follow-up exhibition at a museum. We have shown that using *structured learning*, a *relatable learning context* and *extrinsic motivation* increases both motivation and engagement in participants and allows them to both design and fabricate ECDs. Through the workshop, six artifacts were fabricated by the participants and later presented at the museum. Although all groups were able to design and fabricate displays, we found that ensuring the makerspace had all the tools required ready to use was important to avoid failures. Additionally, we found that teaching material should not only show the correct process but also what happens if that process is not followed.

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Paper D

ShadowLamp - An Ambient Display with Controllable Shadow Projection using Electrochromic Materials

Walther Jensen, Markus Löchtefeld, Hendrik Knoche

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Abstract

In this paper we present ShadowLamp, a lamp concept supporting controllable shadow casting for displaying ambient information. The concept uses electrochromic displays to mask light and thereby allow switching of projected shadows. We implemented a prototype in a hexagon frame with six separately controlled LEDs compartmentalized to casts shadows in 60° angles. Alongside the LEDs, each compartment contains an electrochromic display for shadow control. As a use case we fabricated displays for a children's book and used them to change the shadows as the story progress. The displays and LEDs are controlled by a Bluetooth connected Android application.

Fig. D.1: Example of the two projections one segment of ShadowLamp can produce.

1 Introduction

Ambient displays have been widely researched in the past decades. From entire rooms with the ability to draw attention to parts of the room, to retro fitted furniture that slowly emit changing light to specifically designed ambient displays that subtly project changes in a localized space [1, 2]. Per definition ambient displays are subtle and do not grab attention making them perfect for calm computing [3]. To our knowledge, only one project has utilized hard shadows with discernible projections as an output modality for displaying ambient information [4]. Hard shadows provide a unique ability in that they can project text, icons and graphics onto surfaces, either subtly by fading in the shadows or directly by swiftly changing them. Although ambient displays have mostly used abstract changes, we believe using shadow projections with clear perceptible shapes can open up the possible uses of ambient displays in human computer interaction.

Fig. D.2: Example of a shadow casting lamp. The Shadow Chandelier by Forms in Nature. [5]

Inspired by lamps produced by Pranaya Design, Forms in Nature and Moroccan lamps in general, we sought to create an ambient display that projects hard shadows (see Figure D.1). These lamp designs work by incorporating light masks that would cast hard shadows and produce artisan patterns on the wall or in the case of Forms in Nature an ambient backdrop. The masks are often the frame of the lamps themselves, and can be produced in a variety of ways, e.g. by laser-cutting holes or shapes into the side panels which allow light through and because of this the projections they provide are static. Opposed to this, our concept will use masks that can change between two or more patterns allowing us to change parts of or the entire ambient backdrop. A type of material that allows this are electrochromic materials which has mostly been used to control light transmittance in windows to control the temperature and shade in a room or building. Recently, however, it has become possible to fabricate and prototype custom electrochromic displays using off-the-shelf tools that are thin, flexible and transparent [6]. Using electrochromic displays as masks we are able to create an interactive ambient display that can produce slow changing (30s - 3m) hard shadows for information display. This is possible because each side of an electrochromic display can have a print, where when powered, one print will be near invisible and the other visible. Changing the polarity alternates which print is visible. And because they can be fabricated in non-uniform shapes with nearly any print on them their shadow casting properties can range from small localized shadows to wall sized shadows. Multiple electrochromic displays oriented in differing directions allow us to control the ambient backdrop of an entire room.

In this paper we present ShadowLamp, a prototype that allows control of the ambient backdrop in a room by changing between two sets of projected shadows. The purpose of the lamp is to enable a wide range of use cases that are enabled by fabricating electrochromic displays. We hope that this lamp can help immersion when reading to children e.g. by accentuating parts of the story by projecting shadows on the wall.

2 Related Work

Since the inception of ambient information displays and calm computing research has focused on presenting information in the user's periphery using different types of ambient displays. The information is typically abstractly presented, for example in the form of the brightness of a light or the intensity of a vibration. The research ranges from entire rooms with different types of integrated ambient displays that display information using either light, sound or vibration [1] to very specific use cases such as e.g. an ambient light to help increase physical activity in the workspace [7] or using ambient stimuli to enhance media consumption [8]. In most of the research the ambient display is embedded into everyday objects or aesthetically developed as an everyday object allowing easier integration into homes or workspaces. Gleamy [2], an aesthetically pleasing lamp, subtly change its lighting using transparency controlled panels. The authors present an application case where Gleamy is used as a bedside lamp that visualizes the amount of physical activity by controlling how much of the lamp is shaded. In the Candle Light [9] a candle light is used with rotating cardboard cutouts to provide changeable shadow casting for emotional communication. The candle is connected through Bluetooth to a mobile phone that changes the shadow when receiving messages.

Shadows have been used for centuries in puppet theatre and shadow play for storytelling, however, in human-computer interaction they are a lesser researched subject. Few studies have utilized shadows. In [10], Cowan et al. used juxtaposed hand cast shadows as input in a mobile projector phone system. Häkkilä et al's [9] lamp projected different smileys by rotating the cardboard cutout using a servo motor.

Similar to the candle light lamp we use hard shadows to present our information but without the need for a servo. We do this by changing the state of an electrochromic displays similarly to the panels used in the Gleamy lamp. However, to our knowledge, no ambient display has yet to achieve using a large amount of wall-space as a big information display from a centralized place. Our work differs from previous research in that we can project shadows along all walls in a rectangular room and subtly change them which allows us to ambiently present information on a larger scale.

3 ShadowLamp Prototype

The aim of ShadowLamp is to create an aesthetic night desk lamp with ambient display properties. However, as opposed to previous ambient displays we aim to use hard shadows to control the ambient scenery in a room. Using hard shadows enables us to create specific moods and backdrops. And because electrochromic displays can be fabricated with any design as long as they are within the confines of the individual displays there are many possibilities. The prototype consists of six individually controlled LEDs shining through an electrochromic display creating shadows for the full circumference of the lamp. As the lamp is wirelessly controlled it can be integrated with other technologies such as e.g. an ebook reader where parts of the story is projected through the room, or smart lighting to change the scenery of the room in conjunction with lighting changes.

3.1 Implementation

As seen in Figure D.3, the prototype is glued together in a hexagon shape from 4mm laser-cut plywood. Each section of the hexagon contain a high powered LED and a slide-in holder for the electrochromic displays. The slide-in allow easy change of the displays (see Figure D.4). The six LEDs are individually controlled by an ESP32 and an SX1509 GPIO extender board powers the electrochromic displays. The extender board is needed because each electrochromic display require two connections that programmatically can change polarity. The ESP32 serves as a WiFi access point with a webserver for communication and control.

Fig. D.3: ShadowLamp design with electrochromic displays.

3.2 Electrochromic Displays

The electrochromic displays consist of two sheets of Polyethylene Terephthalate (PET) treated with Indium Tin Oxide (ITO). The designs for the display were printed using electrochromic ink on the ITO side of the PET-ITO by either ink-jet or silkscreen printing. To complete the display a thin spacer material (double sided tape) with a width of 3-5mm was used along the circumference of the display. The spacer keeps the two PET-ITO sheets together and allows electrolyte to be deposited in the center of the display. Which in turn keeps the two ITO layers from short circuiting. Applying a low voltage (1.5v-3v) on one side oxidizes it and reduces the other side. Depending on the electrochromic ink used, the oxidized side will become visible whereas the reduced will become near invisible and changing the polarity to the display changes which side is visible (see Figure D.5). [6]

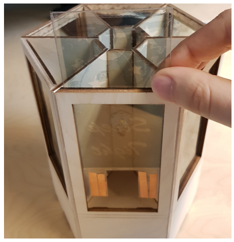

Fig. D.4: The slide-in mechanism allows easy change of the displays.

Fig. D.5: Example of electrochromic display. *Left)*: Side A visible. *Right:* Side B visible. The bright parts let light through and thereby projects intricate shadows.

3.3 User Interface

The interface is programmed in HTML to allow easy control from a wide variety of devices. In the top of the interface a slider controls the overall brightness of the lamp (see Figure D.6). The rest of the interface is split up into segments that control each side of the lamp. Each of these segments contain a slider to control the individual LEDs brightness and three buttons to control the state of the electrochromic display in that segment. The left and right buttons make either of the sides visible and the middle button balances the display making neither side visible.

4 Use Case: Night time reading

As a use case we created six displays for two Smurf [1] stories that projects imagery from the book on the wall as the story progresses. This is to be used for night time bedside reading as one side of the displays projects a starry night sky providing a cozy backdrop for reading. By slowly changing the individual displays to project parts of the story instead of the starry sky (see Figure D.7) we hope to increase immersion in the story and foster interpersonal communication and talk about the story. E.g. "See it's the house where Smurfine lives". Encouraging children to become more active in telling the story is promoted by approaches such as co-reading and dialogic reading to boost language acquisition [11, 12]. The reader is presented with icons in the physical book that match the user interface when a change in the projections is required.

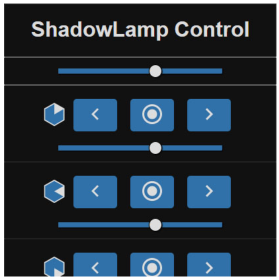

Fig. D.6: Part of the ShadowLamp Control User Interface. Sliders control brightness of LEDs and buttons control which side is visible with middle button making neither side visible

5 Discussion and Conclusion

In this paper, we presented a novel lamp concept that utilizes electrochromic displays to project shadows for ambient communication. Albeit the concept allows easy change of the displays we are aware that fabricating them is not widely understood in the CHI community and is only possible for a limited number of people. We do however believe this paper will help increasing awareness of the opportunities afforded by electrochromic displays. We believe that, in our use case, ShadowLamp provides an interesting and novel approach to increase immersion and engagement through displaying changeable scenes in bedroom settings.

For future work, we wish to run a study with parents reading to their children to verify that ShadowLamp actually increases immersion in bed-time reading and/or engagement in the story telling. In addition to developing other use cases for the lamp.

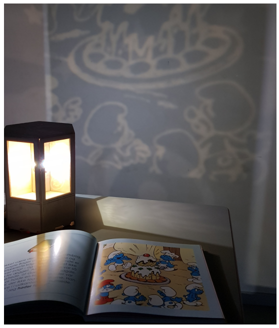

Fig. D.7: Page from Smurf book is projected on wall instead of generic starry sky.

6 Acknowledgements

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Paper E

"Do you think it is going to be the cock?" - Using Ambient Shadow Projection in Dialogic Reading

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Abstract

In this paper we present a lamp prototype that projects controllable shadows to create an ambient backdrop for dialogic reading between parents and their children. The lamp uses four electrochromic displays that allow masking the light and thereby control the shadows that are projected upward onto the ceiling. The displays can switch between general ambience picture and a certain story point in a Smurf book. These displays were used in a reading study with parents reading for their children and a focus group session. The results indicate that the lamp helped in spurring interest and a dialog about the story being read. The used technology proved to be implicitly triggering questions and discussion about the story by creating suspension when switching between the different shadows.

1 Introduction

Language acquisition in young children is important to their development in later literacy skills and language. One method that has proven to effectively increase acquisition is dialogic reading where the storyteller, typically adult, interacts with the children by prompting questions as part of the reading or even letting the children be the storyteller during a reading session. However, as more families get access to computers and tablets with e-books and interactive applications, the children start to divide their attention between the technology and the story that is read to them. This might be one of the reasons that the change to e-books and interactive applications has shown to have a negative affect on story comprehension [1]. Prior approaches to support dialogic reading through technology have focused on e.g. making the stories interactive so that e.g. the children's pointing would have an effect [2] or through supporting the reader with alternative words or questions [3]. Here we want to follow a slightly different approach, in which we try to introduce technology without distracting the audience by projecting shadows of story points on the walls or ceilings. We hope that this prompts the children to ask questions of or reflect on what they see, which can augment and create interest in the story during reading.

To realize this we utilize a combination of electrochromic (EC) displays and LED's to provide background illumination for reading while simultaneously projecting shadows that create interest in the story being read. An EC display can consist of two graphics printed on a transparent substrate with a conductive layer, and powering using a low current will make one of the graphics visible while the other will become near invisible. Which graphic is visible depends on the polarity of the current [4]. As EC displays can be transparent they also can function as light masks; therefore, one display can provide changing shadow projections and potentially project different illustration from a story.

In this paper we present a novel pervasive lamp prototype that consists of a 3D printed lamp casing to provide soft illumination and electrochromic displays to project shadows. Wireless enabled hardware drive the lamp through a web interface allowing a wide range of devices to control it. We fabricated four electrochromic displays that each in combination with LEDs project either a pattern with stars or an illustration from a children's book.

Fig. E.1: Lamp lighting up room while projecting shadows.

2 Related Work

Reading and storytelling to children is an important part of development of literacy skills and language [5, 6]. Feedback, utterances and prompting from parents during reading sessions has showed increased effectiveness in language development of the child [7]. Dialogic reading is one method of telling stories to children and is proposed to have three levels: *1)* introduction of new words, *2)* practice and expansion, and *3)* relation [8–11]. In the first level the reader asks "wh" questions to the new words introduced during reading e.g. "*what is that?*", "*what color is this?*". When the child has repeated the new words several times the reader can proceed to the second level where open-ended questions are asked e.g. "*What do you see on the page?*". Finally the third level asks questions to the plot or characters of the story e.g. "*Why is he/she happy?*", "*What happens next?*". Additionally the child should be asked to relate the story to personal experience. With the increase in children who has access to electronic devices such as smart phones and tablets researchers have investigated their use for story telling as these devices lend themselves well for it. However, studies have shown that the electronic features deflect the attention from the story resulting in interactions where the reader's prompting is more likely to be "*Don't click that*" than the previously mentioned dialogic related prompts [2, 12–14]. However Nadarajah et al. also demonstrated that technology can support the person that reads through facilitating support with alternative words and questions [3]. The here presented prototype builds on that idea, the ambient backdrop that we create through hard shadows, is meant to facilitate a conversation between the child and the reader about the content of the story.

In the field of calm computing, researchers have focused on using different types of ambient displays to present and communicate information. These displays mostly present information abstractly by either light, sound, vibration or movement. One of the earlier projects ambientROOM, fitted an office room with a range of ambient displays to provide information for a personal interface environment [15]. Fortman et al. focused on embedding the ambient information into everyday objects e.g. an ambient display desk lamp for workspaces that notify the user when to get physical to increase health [16]. The aim for embedding the ambient display into everyday object is to allow easier integration into workspaces or homes. Gleamy [17], a lamp designed to be aesthetically pleasing provides changing light by altering the transparency of it's frame. As the frame is composed of 40 individually controlled triangles it can provide a wide range of information either statically or through animation. Using Gleamy to show physical activity at the end of the day was one suggested application case. Our work differs from these previous ambient display approaches by providing an ambient backdrop that contains story related shadows. We aim to encourage an active dialog instead of just displaying ambient information, nevertheless, it is still meant to be ambient and not the focus of attention.

In human-computer interaction, shadows are a subject that has not received much attention. This, in spite of, puppet theatre and shadow play having been around for centuries [18]. To our knowledge few studies have researched the use of shadows for interaction. One study presented ShadowPuppets, a system that allows casting shadows as input for a mobile projector phone [19]. Interestingly, this use of shadows

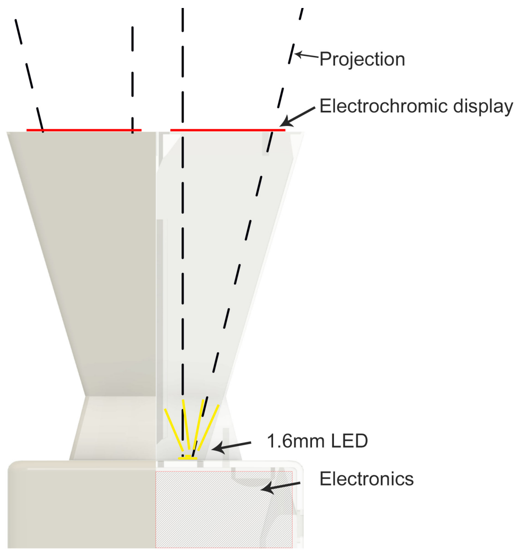

Fig. E.2: Lamp design. Left: No cross section view. Right: Cross section view.

as an input is intuitively easy to understand as everyone can use they hands for casting shadows as long as there is light. Maybe the closest related to the work presented in this paper is the approach of Häkkilä et al. [20, 21]. They presented an ambient display that uses the light from a candle and cardboard cutouts to project shadows. The candle light display projected smileys for emotional communication and rotated the cardboard cutouts to change which smiley to project. A Bluetooth connected smartphone would control which smiley to project based on incoming messages. Our approach is very similar but utilizes electrochromic displays to mask the light for the shadows and can be controlled similar to the panels in Gleamy's lamp. Furthermore, by using multiple separately controlled electrochromic displays we can present a range of individually controlled shadows.

3 Concept and Prototype

The concept for the lamp is to provide ambient illumination in the form of a shaded bed table lamp while being able to project hard shadows onto the ceiling that work as an ambient backdrop. Through the projected images we hope to encourage a conversation about the story which further can stimulate and support dialogic reading. Illuminating with soft light should provide enough light for reading a story without needing to add extra lights in the room and without disturbing the shadow projection abilities of the lamp. The lamp projects four separate shadows onto the ceiling arranged in a two by two grid projecting one big rectangular shadow with each separate projection switchable between two shadow patterns. The frame of the lamp contains four holders for electrochromic displays that enable the switching of shadow patterns. This allows

Fig. E.3: Electrochromic display designs. *Left:* 2by2 grid shows the story illustrations. *Right:* 2by2 grid shows the generic stars.

the lamp to be used with different stories or for different purposes than just augmenting points in a read story.

For the projection of the shadows we use electrochromic displays which consist of two sheets of Polyethylene Terephthalate (PET) treated with Indium Tin Oxide (ITO). The designs for the display were printed using electrochromic ink on the ITO side of the PET-ITO by either ink-jet or silkscreen printing. To complete the display a thin spacer material (double sided tape) with a width of 3-5mm was used along the circumference of the display. The spacer keeps the two PET-ITO sheets together and allows electrolyte to be deposited in the center of the display. Which in turn keeps the two ITO layers from short circuiting. Applying a low voltage (1.2v - 3v) oxidizes one side and reduces the other side. Depending on the electrochromic ink used, the oxidized side will become visible whereas the reduced will become near invisible and changing the polarity to the display changes which side is visible [4]. The length of the time it takes to switch can be modified by altering the amount of the applied voltage. We opted for a longer transition period so that their would a form of suspension and some time to switch focus while reading.

As seen in Figure E.2, the prototype consists of a white frame 3D printed in three separate parts. The bottom part provides enough space to contain the electronics that power and control the LEDs and EC displays. The middle part is 13.5cm in width and depth and is 15cm tall with thinly (0.8cm) printed outer walls allowing light from the LEDs to bleed through providing soft illumination from the circumference of the lamp. At the top surface of the middle part electronic connection points in addition to insets allow EC displays to be easily switched for different books. The top part has the function to keep the EC displays in place and electronically connected. The total height of the lamp is 21cm. This provides overall clear shadows at 2-3m distances

For electronics we used an ESP32 connected through I^2C to an SX1509 GPIO extender board. This provides wireless connectivity with enough outputs to control both LEDs and EC displays. Four high powered 1.6mm LEDs (max 350mA) are connected through MOSFETs to the ESP32's outputs and the EC displays are connected to the GPIO extender board. The GPIO extender board is needed because the EC displays require two controllable connections to provide bidirectional switching of the display. The ESP32 functions as an wireless access point that provides a HTML web interface to control the lamp. To this the user can connect via a smartphone and select which screen to switch.

3.1 Shadow Pattern Designs

We used the "The best Smurf stories" compilation book as it lends itself to reading and story-telling in a dialogic setting and has illustrations that easily transfer to shadow patterns. The illustrations were traced to a vector graphic and resized to fit in a 5 by 5cm display (see Figure E.3). Alternative to the illustrations from the book are a side with stars to create an cozy ambient setting where each display will change into the corresponding illustration from the book as the story is being read. To ensure the reader know when to switch a specific projection from stars to story illustration, markers were added to pages were the reader has to interact.

4 Focus Group

To evaluate the concept and identify usability issues we organized a focus group session. The goal of the focus group was to get feedback from users on usability as well as experiences from parents reading to their kids besides more general questions towards the prototype and idea.

Procedure

The following tasks were followed: consent form and background questionnaire, short open discussion on their experiences reading to their children, showcase and explanation of the lamp, discussion on the lamp and its aesthetics, trying out the lamp control interface, and finally open feedback.

Participants

We invited six (5 female, 1 male, average age 47.3 (sd=9.8)) participants for the study group. All have children and four of the participants have two or more children and have read to them in the past. Two mentioned that they even have used props (toys, cutouts, models) as part of their reading and one has used electronic device to support reading. The focus group took approximately 30 minutes, was video recorded and facilitated by one researcher. The video material was analyzed and coded afterwards. The participants were asked if they pursued some form of dialogic prompting when reading stories with their children or whether they only read out loud. All the participants in one way or another talked with their children about the stories. E.g. "*I read out loud and then we always talked about what it said and the pictures*" followed by another participant "*And that could also start conversations about other things*". When asked whether there were things in the books that made them more popular

Fig. E.4: Focus group in progress. Participants trying out lamp control interface while being very interested in the display technology used to project shadows.

(story or amount of pictures), story was the most prominent answer with relatable books being most popular "*We've read a lot of Villads from Valby. They can relate to that because it is about a schoolboy*". None of the participants were aware of dialogic reading as such and that they, to some extend, subconsciously had used this technique with their children in prompting "wh" question and discussed relatable plot points.

The facilitator explained the purpose of the lamp while showing how its lighting and shadow projection functions. Some of the shadows were shifted during this presentation displaying the time it takes to shift from one shadow pattern to another. The connection to the Smurf book was explained while the display was shifting. The participants were reluctant towards the idea of themselves using the lamp as they would have to use a smart phone to switch the shadows. They saw this as a break in the scenario of reading and feared it would tear the concentration from the story. However, they suggested adding physical buttons to the lamp so either they or their children can switch the displays: *"I'm thinking in terms of shifting shadows, it would be smart if there would be a button on the lamp"*, add sound effects (background music, jungle sounds etc.) that fit the story being read to increase the immersion: *"Have you thought about adding sounds to it? Not text but music, sound effects etc"*, or automating the switching of the shadows directly from the pages of the book e.g. "*Can't you just put it into the pages?*". If any of these features exists in the lamp they could see themselves using it. Additionally some suggested using children themes for the lamp either a super hero or princess look. Something that would fit in a child's room.

Following a short description of how the control interface works and how the reader can see in the book when to use it; the smart phone controlling the lamp was passed around for the participants to try out (see Figure E.4). When asked whether they would change anything in the interface, they all agreed that due to the minimal amount of buttons present it is easy to understand. However there were suggestions to change the icons on the buttons to resemble the actual graphics being projected: *"You could use stars or something that reminds of the pictures from the book"*, *"Then you aren't* *in doubt where which button you have to click"*. Another problem that was brought up is the handling of a book while operating the smartphone. This was deemed to be a potential issue. As already mentioned during an earlier question, they reiterated that the lamp should somehow function automatically through flipping the pages in the book. Furthermore when asked to operate the lamp by itself they had issues orienting the lamp correctly and align the projection onto the ceiling.

Discussion

While the general concept and idea was deemed to be acceptable in terms of interaction with the prototype several shortcomings where revealed of the prototype. The first issue that participants faced while using the lamp is the orientation of the lamp towards the ceiling. Therefore we added for the second version an indicator which direction should face towards the users in from of and arrow to the lamp. The second issue was the user interface. While the participants reported no problems with respect to connecting to the lamp - switching the focus from the book to the smartphone while reading was flagged as a potential issues. The focus group participants voiced this concern from the very beginning. Several alternatives were mentioned by the participants that are feasible. Using buttons on the lamp could be problematic if it is out of reach, and having it directly integrated into the book would require some form of wireless technology inside the book hich would increase the cost of each book. Therefore we designed a clip-on element that can be attached to the book. This clip-on consisted of four buttons, a small battery and an ESP32. The ESP32 would connect to the lamp wireless and by pressing the button the displays would be switched.

5 Reading Sessions

To evaluate the potential of the ambient shadow projection to stimulate dialogic reading we facilitated four reading sessions. Focus of this sessions was to analyze whether children would engage with the projection and voluntarily use them as a mean to ask questions or stimulate discussions. For this we recruited four university employees (3 female) to use the lamp during their night time reading with their children. All participants used the lamp while reading to one or two children at a time. The age and gender of the children are as follows: 4 female (ages: 4 5, 6 and 9) and 2 male (ages: both 8).

5.1 Procedure

For the reading sessions the participants would read the Smurf stories to their children using the lamp for shadow projection while filming the session at their own home. Before the participants would take home, the lamp, book and a video camera, they received a demonstration on how to connect and use the interface that controls the lamp as well as the markers in the book that indicated a shadow switch. At this point the participants also were required to try it out themselves as part of a short training. Furthermore the participants were instructed on how to use the camera and to make sure that the projection as well as the gestures of their kids would be in the camera

Fig. E.5: One child pointing towards ceiling in excitement of the changing shadows.

field of view for later annotation (compare Figure E.5). After their reading session a follow up feedback session was conducted which was audio recorded.

5.2 Results

Overall all but one child (female aged 4) actively engaged with the projection in one way or the other. The reason for this one child not to engage might have been due to the fact that the child's field of view was not aligned with the projection. As we did encourage the parents to not steer the kids attention towards the projection we expected to have these observations as well. Another child (male aged 8) did observe the shadows and realized that they changed but never actively engaged with his parent about during the reading. Only after the reading was over the child reflects on the shadows. The reactions were limited to uttering words such as "That's Smurf town" and "We have heard about the rooster, the cake and the egg" while pointing at the different shadows.

All other children actively engaged with the parents about the changing of the shadows in a matter that is preferable for dialogic reading. The interaction that triggered the change created both anticipation and excitement in the children and a slowdown in the reading. After the first shadow had changed the children knew that the shadows would change when the parent triggered a button which prompted either pointing or looking up at the shadows with utterances such as *"It's up there"* while pointing or *"This is so strange"*. Additionally it also encouraged dialogic prompting from the children throughout the reading. Speculations about what change the interaction will trigger such as *"Do you think it is going to be the cock?"* or discussions before the switch was completely finished such as *"What is it?"* followed by *"Aah it's a cock"* or *"What is that?"* could be observed in all sessions. In two sessions when the last shadow had changed and the parent said there were no more shadows to change the children were let down and uttered words such as *"But aren't there more?"* or started to look directly at the lamp and into it to see the displays changing the shadows.

In the follow up feedback session all parents mentioned that it worked well but that there were things that should be solved better. Two parents suggested automating the changing shadows based on the current book page or when flipping the page. Three parents also mentioned that ideally there should be more shadow animations, so that the time between two triggered animations would be shorter and the shadows could become a more integrated part of the story telling. Two participants explicitly mentioned that the 5-6s switching time of each of the displays was well chosen as it created a suspension that would automatically prompt discussion between everybody about what would appear. One parent mentioned that it was a bit difficult to see the shadows due to having an uneven ceiling (see Figure E.6) and because the power cord was too short and the lamp had to be placed in a non-ideal position.

6 Discussion

Based on our evaluations the concept of using EC displays to project and ambient backdrop of shadows for dialogic reading as such matched well with current practices and supports the process by prompting dialog about the read story. The pointing of

Fig. E.6: Both parent and children looking up to see shadow change.

the children during the reading sessions, and the naturally emerging discussions and questioning, without the parent having to prompt questions are a clear indicator that the idea of the ambient background projection worked well.

The suspension that is created when the parent triggers the change in addition to the time the displays need to switch between their states seem to work in favour as it spurred discussions as soon as the children understood the workings of the lamp. Even if in future iterations of the prototype the EC displays are replaced with another technology, our current findings strongly suggest that there should be a certain switching time introduced to create suspension. The amount of projected shadows was deemed as too low, both by parents as well as children. They felt that there was too much reading-time between two display switches. While our current prototype does not support more than 4 displays, other ways of constructing the EC displays could allow for more elements that change or only partly change [4].

Additional audio elements that have been brought up in focus group where not specifically mentioned by the parents. However automatic switching when flipping has been mentioned by a parent. This would though require some form of wireless technology inside the book (e.g. Zig-Bee) which would increase the cost of each book. A connected e-book (e.g.on a smartphone or tablet) that either switches automatically would solve that problem. However, given that the explicit interaction to switch the display often triggered a dialog, we would advice against complete automatic switching. Triggering the switch could also be done by the kids and be used as an additional dialogic reading element.

7 Conclusion

In this paper, we presented a concept and prototype of a 3D printed pervasive lamp that provides soft background illumination while being able to project shadows onto the ceiling. The lamp is wirelessly controlled by either a web interface allowing any device with a browser and WiFi or a clip-on for books to control the lamp. Our evaluation indicate that projecting book illustrations as shadows increase interest and dialogic prompting during parent - children reading. Especially the suspense that is created during the switching prompted a dialog and should be taken up into future implementations of this concept.

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Paper F

VitaBoot - Footwear with Dynamic Graphical Patterning

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Abstract

VitaBoot is a footwear concept incorporating dynamic graphical patterns which indicate the wearer's activity level. Whilst shoes are an important element in fashion wear and a lot of research has focused on shoes as input devices, comparable few concepts have explored the potential for their use as an output space. We created a boot design that incorporates dynamic patterning through the use of electrochromic (EC) displays embedded in the surface material. The boot was designed and constructed from scratch, using a faux leather material, ensuring the overall aesthetic of the design, including the integration of the required control electronics and power source. The boot connects wirelessly to a chest-worn heart rate belt, and pattern changes indicate when the wearer's heart rate is above a predefined threshold. VitaBoot demonstrates the potential for dynamic shoe patterning for aesthetic or functional means, and the suitability of flexible, low-power EC display technology in this domain.

1 Introduction

Wearable technologies, in the form of smartwatches and wristbands are nowadays commonplace. Fueled by the availability of smart textiles, flexible computing and decreases in size and power consumption, concepts integrating various input and output mechanisms into garments are appearing. Whilst much work in the area of smart clothing has focused on garments, such as dresses, shirts and jackets, relatively less researched items include shoes and accessories such as handbags and jewelry. In this paper, we focus on shoes as a wearable computing platform, more specifically, on their use as a visual output platform through the integration of ambient display elements.

Directed by Weiser's calm computing vision, we aim to utilize the output modality of a clothing-integrated computational system as a fundamental design element in the overall aesthetic of the clothing. Due to their relative ease of integration and their colorful vibrant output modes, a majority of previously presented smart clothing design pieces have utilized light-emitting LEDs as the output technology. Whilst such approaches are suitable as exhibition pieces, less luminous approaches are more suited for daily wear, complementing existing design lines, rather than the light being an overpowering element. Thus, we focus on the use of Electrochromic (EC) display technology, which is non-emissive and particularly suited to wearables applications due to its flexibility, ability to be fabricated in non-rectangular shapes and its extremely low power requirements. Considering shoes, with their 3-dimensional curved surfaces, such flexibility is essential to avoid limitation in the placement of display elements.

In this paper, we present VitaBoot, footwear which provides the wearer with ambient notification of raised heart rate, measured by a connected smartwatch or chest-belt sensor. VitaBoot encourages the wearer to take bouts of beneficial light activity during the normal day, such as walking up a flight of stairs, which is then rewarded with a visible pattern change. The shoe is designed as a fashionable shoe for daily wear, the ambient nature of display complementing the aesthetic, rather than drawing attention from bystanders.

Fig. F.1: Raised heart rate indication in activated and deactivated states.

2 Related Work

Wearable Displays

As well as acting as data collection devices for activity tracking and bio-data, wearables have also been explored as output devices. Schneegass et al. present a design space for such, including e.g. who is viewing the display, what is the display content and where on the body it is situated [1]. Wearable displays have been incorporated in garments [2], and in accessories such as brooches [3], or handbags [4].

Smart Footwear

Prior works in the area of smart footwear have primarily explored instrumenting the foot with sensors e.g. for sports and medical applications [5]. Few commercial examples of shoes as an output space exist, beyond the novelty LED soled children's shoes, that illuminate with each step. A design space for shoe integrated displays has been presented by Colley et al., considering dimensions e.g. if the display is targeted for visibility during wear, or when the shoe is removed [6]. An initial prototype utilising EC displays in a running shoe has been presented by Müller et al. [7]. However, the approach of attaching displays to an off-the-shelf base shoe prevents the achievement of a holistically designed piece. In Nachtigall's EVA mocasin [8] methods of indicating the shoe's wear state are integrated into the design of the shoe.

Our Contribution

Whilst shoes and other footwear are a large and important segment of the fashion market, they have been so far little addressed as a space for dynamic visual output by the interaction design community. This reticence is likely fueled by the challenges of the space, presenting curved and flexible surfaces, difficult to work construction materials (such as leather), small spaces for embedding electronics and the need for a high level of prototype robustness to support normal wear. With Vitaboot we add to the few presented examples of visually adaptive footwear, highlighting the potential of addressing the task of dynamic shoe design from first principles, rather than as an addition to an off-the-shelf base model. The characteristics of the EC displays in our prototype enable going beyond the restrictions of rectangular rigidity faced by prior research (e.g. [9]).

3 VitaBoot

With similar motivation as Devendorf et al.'s "I don't Want to Wear a Screen" [10], we aim to create a wearable that prompts the wearer to include new experiences in their everyday life. We explore the potential of shoe based visualization, which is non-distracting, yet easily glanceable by the wearer (perhaps with small leg movement) in the majority of daily life contexts. Targeting to encourage the wearer to incorporate light exercise in their routines, such as taking the stairs or fast walking between appointments, we selected that the shoe should provide indication of elevated heart rate (measured by a separate body-worn sensor).

Exertion during exercise is normally indicated by heart rate zones with each zone providing different health effects. Any exertion above a certain zone, however, provide health benefits in general and therefore we decided to provide a single state indicator that the wearer could affect in real-time shown through their actions. A pattern change on the shoe provides motivational feedback for the wearer's actions (Fig. F.1).

Fig. F.2: VitaBoot worn and showing activated graphical patterning.

3.1 Design Approach

As the start point for the design, we selected to utilise two existing toolkits, ONEDAY Shoes [11] and the TransPrint electrochromic display method [12]. The ONEDAY Shoes kit provide a pair of shoe soles, a set of downloadable templates and instructions on fabrication and assembly. TransPrint provides an easy method to design, print and fabricate transparent flexible free-form electrochromic displays; utilizing PET-ITO film, EC ink and electrolyte. As such elec-

Fig. F.3: Final prototype with graphical pattern active.

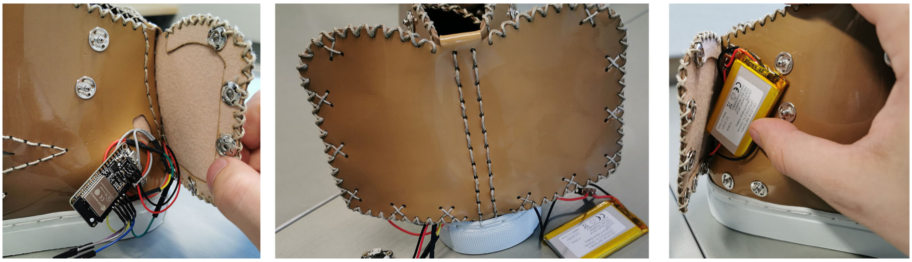

Fig. F.6: Electronic pocket design. Left side contains ESP32 board and right side the battery. Wires are hidden under the pocket flaps.

trochromic displays are flexible and can be fabricated in a free-form shape, they are a natural fit as embedded ambient shoe displays.

3.2 Design Process

As we were aiming for a casual-retro inspired look, a faux leather material with a light-to-dark brown gradient was selected as our construction material. Based on the ONEDAY shoe templates, an initial design was created and the required panels to construct the shoe, including all the needed holes for sewing, were laser-cut from the material (Fig. F.5). With this initial prototype, several different locations and formats for the dynamic graphical display area were explored. Approaches using typical segmented-bar type activity visualisations were rejected, as not contributing to the overall aesthetic of the footwear. Instead we settled on a concept inspired by 1980s-era workouts "*feel the burn*" and evolved a dynamic graphical motif in the shape of a flame (Fig. F.1).

Fig. F.4: Graphic design iterations.

Fig. F.5: Side panel iterations of the VitaBoot during construction

The size and placement of the dynamic graphic display element was constrained by the construction of the electrochromic display element, requiring a border area for the counter-electrode (CE) and 4-5mm non-functional adhesive strip. In our design, the display was located behind a cutout in the shoe's outer surface, such that only the central flame area of the display was visible, the CE and adhesive border being masked from view (Fig. F.7).

We sketched several different designs for the dynamic graphical element, (Fig. F.4), eventually settling on a simplified flame pattern design that was in keeping with the overall retro design direction of the piece (Fig. F.4, right). The

Fig. F.7: The electrochromic display design, showing counter electrode (black bar around flames), border areas (grey) and connection areas (dashed).

electrochromic display element was then constructed, following the guidelines of the TransPrint method [12]. Three layers of PEDOT electrochromic ink were used, printed with an ink-jet printer and oven dried after each layer.

To enable the shoe's functionality, a microcontroller and battery power source were also required to be integrated into the shoe. Here we needed to meet the requirements for size and rigidity of the electronic elements without degrading the overall aesthetic of the shoe. For example, locating the electronics in the insole of the is not possible due to the flexibility of that area during normal wear. Thus, we created a pair of secondary surface flaps on the heal area of the shoe, into which the electronics and battery were inserted (Fig. F.6).

3.3 Technical Implementation

The system was controlled by an Adafruit ESP32 Feather microcontroller, programmed to connect to a BLE enabled heart rate monitor via the Bluetooth GATT heart rate protocol. One EC display was fitted on each side of the shoe and driven with 1.5V, the polarity being reversed to change the display state. When connected to a heart rate monitor, the display state is switched such that the flame pattern is visible when the heart rate is above a threshold of 100bpm. For heart rates below this threshold the flame pattern is not visible.

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Paper G

Hybrid Settlers - Integrating Dynamic Tiles into a Physical Board Game using Electrochromic Displays

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Abstract

In this paper we present a novel method of hybridizing physical board games by adding dynamic and digitally controlled fields utilizing electrochromic inks. In particular we built electrochromic displays that fit the hexagon fields on the Settlers of Catan board game and thereby added the ability to change a fields resources during game play. In this paper we report on the prototypical implementation and two preliminary studies that indicate how these dynamic fields can increase the excitement and reward of playing the game.

1 Introduction

While digital games are increasing in popularity and market share, physical board games still enjoy great popularity due to the tangible elements and social aspects [8, 11].

Fig. G.1: Hybrid Settlers. Settlers of Catan with four dynamic tiles.

In recent years the hybridization of board games - introducing digital aspects into the physical gameplay - has been investigated [7]. Not only have mixed reality approaches [2, 3] explored, but even products such as Hasbro's zAPPed range of boardgames been released to the market[1]. These games integrated the users mobile device into the game play, but have however, been discontinued as of now. This might be due to the need of an expensive additional device.

In a 2004 study, manufacturers, players and game authors were interviewed and asked about potential board game extensions. The results identified a digitally controlled changing gameboard composition as one of the most sought after electronic enhancement [1]. While physical bricks could enable this, they would require some remodelling which might disturb the game flow. A complete digital gameboard (e.g. an OLED display or a projection) would allow for full flexibility but also would remove some of the appreciated aspects of board games as we all as require complex control mechanisms.

In this work we propose the usage of electrochromic ink as a low-cost and low-energy alternative to create dynamic gameboards. In recent years it has become possible to fabricate transparent and non-uniform displays using electrochromic ink [5] and they have been used for a variety of different application ranging from simple paper augmentation as in game cards [5] to complex wearables [4, 5]. This display technology allows creating tangible and dynamic elements for board games that can be created in different forms and have relatively small requirements in terms of needed control circuits and energy supply.

To demonstrate the viability of this technology in board games we present Hybrid Settlers, an augmented version of Settlers of Catan in this paper. It features dynamic tiles which randomly change board game tiles during gameplay or manually by using a Bluetooth enabled controller. We present the prototypical implementation as well as an initial evaluation that explores whether adding dynamic tiles increase entertainment value and/or excitement. Our findings suggest that there is a benefit in adding dynamic tiles to increase excitement and reward.

2 Related Work

While there has been extensive evaluation of user experience in digital games, comparably little work has focused its attention on board games or hybrid board games in HCI. In this work we particularly focus on eurostyle board games that tend to favour player interaction and strategic thinking over luck. The differentiation factors that are particular about these games such as social interaction and materiality of the boardgame have been well documented and highlighted by Woods [11]. Rogerson et al. similarly found, in their investigation into the enthusiasts' culture of boardgamers, that the material aspect of the game even down to the box of the game, as well as the environmental setting are important aspect of the overall experience [8]. These works suggest that when adding digital elements not to interfere with the materiality and social aspects of the board game.

[1]https://newsroom.hasbro.com/index.php/news-releases/news-release-details/game-life-monopoly-and-battleship-get-zapped-new-revolutionary

Several different approaches to hybridizing board games have been investigated, especially using Augmented- and Mixed Reality. For example, Huynh et al. combined smartphones with physical game pieces to create an AR tabletop boardgame, where several players have to cooperate to achieve the goals [3]. Echtler explored the possibility of live streaming gameboards and projection based AR to allow hybrid board games with remote players [2]. However, these approaches require extra devices that would create different experiences for different users or heavy instrumentation of the environment. Both approaches might be less favourable in a commercial setting.

Very recently Kankainen and Paavilainen presented 17 guidelines for hybrid board games that they derived from an iterative workshop process with experts [6]. As discussed later we follow (when applicable) their suggestions in our design. Another aspect has been uncovered by Wallace et al. [10]. They found in their investigation of level of automation which more accurately mimics physical board games, that reducing the automation of their digital tabletop game resulted in higher understanding of the state of the game. We decided therefore to limit the autonomy of the digital aspect of our hybridized board game to not take too many deviations from the original game.

3 Hybrid Settlers

3.1 Settlers of Catan

We chose Settlers of Catan for hybridization as it is a highly acclaimed multiplayer and best selling board game [11]. The players settle on the uninhabited island of Catan and has to build settlements, cities and roads by tapping into the natural resources. Two six-sided dice control the resource production and building principalities gain the player's victory points. The original board game consists of 19 hexagonal tiles that each have six natural resources. Each tile has a number between two and twelve assigned to it that the player must toss with the dices to earn the respective resource. The only exception is the desert tile which does not give any resource. Winning the game requires accumulating the required victory points.

One token in the game functions as a robber token, where if 7 is rolled by a player, the token must be moved. It is initially placed on the desert tile (located in the center) and when moved the resources of the tile it is moved to are no longer produced while the token is on the tile. The token also allows the player to steal resource cards from other player's settlements or cities adjacent to the where the robber token is placed. If any player has more than 8 resource cards when a 7 is rolled they must discard half of their resource cards.

3.2 Dynamic Tile Design

Electrochromism is the ability of some materials to change their optical properties through chemical oxidation or reduction when an electric current is applied to them. Usually the change is from a color, e.g. blue to a transparent state. The displays do not emit any light, which makes their impression more like changed print. We

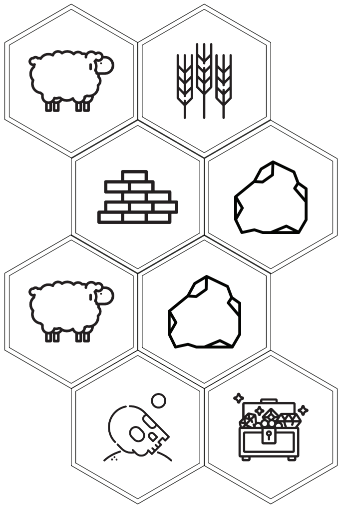

Fig. G.2: Dynamic tile designs. *Row 1*: wool and grain, *Row 2*: brick and ore, *Row 3*: wool and ore, *Row 4*: desert and golden chest

follow the process described in [5] and used the Ynvisible Ink-Kit[2] to produce the displays. Due to the limitations of electrochromic inks the designs for the dynamic tiles are iconography's of resources. Four icons were designed to represent the following resources: wool, grain, brick and ore (see Fig. G.2, row 1-3). These dynamic tiles will function as regular resource tiles that can dynamically change the resource during game play. To add an extra dimension to the game, the desert tile was also made dynamic but instead of only being a desert a possibility of bonus was added to the tile in the form of a golden chest (see Fig. G.2, row 4). The golden chest allows the players to select which resource the tile to produces.

The aim behind this design is to add another semi-strategical element towards the game. While inherently Catan is a game that requires strong collaboration between the players, in terms of trading resources etc. we hope that the introduction of these dynamic tiles will not only be used for the players own good but also to maybe harm others and create some artificial competition [9]. The design of these tiles is also in alignment with the guidelines by Kankainen and Paavilainen [6]. They are designed to add extra value, in case of a technical failure it is easy to recover from and the used technology is self contained and should be long-lasting. Furthermore, the general design as well as the rules are meant to be easily customizable. The tiles also keep the tangibility of the original and are completely integrated.

[2]https://www.ynvisible.com/ec-kit

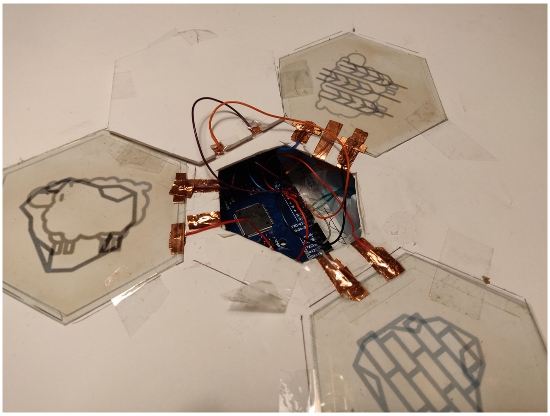

Fig. G.3: Three dynamic resource tiles connected to the electronics in the hole. Center tile is flipped over to expose and show electronics.

3.3 Implementation

A hexagonal shaped hollow box made of foam board was built to place the board game on and hide the electronics that drive the dynamic tiles. The roof of the box had a hole where the center tile of the gameboard is located which allowed wires to the dynamic tiles to be hidden (see Fig. G.3). Four electrochromic displays were fabricated with the same size and hexagonal shape as the original Settlers of Catan tiles (see Fig. G.4). Each display requires two general purpose input/output (GPIO) pulse width modulation (PWM) pins and therefore an Arduino Mega was used power the displays. Pulse width modulation was needed to enable powering the displays with different voltages. The Arduino was coded to randomly change the dynamic tiles. Every 30 seconds the algorithm would run a random check which had a 50% chance of changing the tile, if a tile was changed it would stay in it's state for 45s to 180s. After the first preliminary experiment a physical Bluetooth enabled controller with three buttons was developed that allowed the players to manually switch the dynamic resource tiles once per round.

4 Preliminary studies

To investigate how the hybridization of Settlers of Catan changes game strategies and enjoyment of the game, we conducted two preliminary studies. In the first one the tile would change randomly and in the second one we would give the participants the possibility to change the tiles manually.

4.1 Participants

As participants we recruited members of a local board games group to participate in our preliminary studies. Our requirement was that they had extensive experience

Fig. G.4: Fabricated dynamic tile with brick and ore resource. Ore is visible and thereby active.

playing Settlers of Catan. For both iterations of the game we had the same three players (two male, one female), aged 23-27, play the game.

4.2 Procedure

We conducted both studies in a living room setting with two observers taking notes. One moderator briefed the participants on the study. To reduce game time players won the game when eight points had been obtained as opposed to the standard ten points. In the first study we asked the participants to first play a game of regular Settlers of Catan followed by a game of Hybrid Settlers in which the tiles would change randomly as described above. In the second study we again asked participants to play two games, for the first play through the participants could change the resource of the dynamic tiles using the Bluetooth controller if they rolled the number placed on the tiles and for the second play through it required rolling a pair. We conducted a semi structured interview session when the second play through was finished to receive feedback on their impressions of the differences between the two play through.

5 Results

The general feedback from the first study was that the participants preferred Hybrid Settlers to the original game because the dynamic tiles added randomness to the game and removed the focus a bit from the usual strategies. When asked about the number of dynamic tiles they responded that no more than one more dynamic tile should be added: "*I will say, no more than one more display. It's also nice that not all the resources*

Fig. G.5: Game board during play through of Hybrid Settlers in the study.

can change.". Furthermore, they added that other parts of the game could potentially be made dynamic as long as there were still tangible elements in the game, such as buildings, development cards and resources. For the center tile (desert and golden chest) they were particularly positive as it changed from being mostly a negative outcome when a seven was rolled to now having the potential of being a positive outcome: "*Even though I did not have a house on the desert piece, I think it was exciting when someone rolled a 7. It will becomes a little more positive to roll 7 instead of the 7's only being negative.*". Additionally, they expressed that risk versus reward of the center tile made them build towards it instead of avoiding it.

For the second study the participants expressed that adding the controller further increased the excitement of the game due to being able to manipulate the resource intake of the opponents by changing the tiles into a resources they did not themselves need. They preferred the single toss game to the pair game because it allowed them to more easily disrupt opponents game by changing tiles they were using. This also showed in the play through in the form of small battles between opponents trying to disrupt their resources. Additionally, being able to change their own tiles to something useful brought more excitement to the game play. Furthermore, we saw an increase of 25% in dynamic tile changes in the single toss game versus the pair toss game.

6 Discussion

Albeit it is possible to hybridize all tiles on the game board our participants indicated that some of the original game should stay the same, this is also in line with the guidelines in [6]. We believe there are two reasons the participants do not want every tile to be dynamic. *First*, the hybrid tiles are very primitive in graphics, meaning the original style is missing which would result in losing all the detail of the original game board if all tiles were converted to dynamic tiles. *Second*, keeping some of the game board in its original game style ensures the nostalgic feel of the game is preserved. Keeping the nostalgic feeling of the game was the same feedback [1] received after having digitized the game using LEDs showing that as long as some of the game is the same players do not mind digitizing.

Another interesting aspect in Hybrid Settlers that we noticed was how the option to directly disrupt the opponents game increased the excitement. The players would get personal and start small bouts of disrupting each others resource generation and at times more or less focus solely on disrupting a specific players resources or team up with another player to focus on another player. We believe this ability adds more strategy options to the game that are different than what is currently possible using the original game. In general it seems adding dynamic elements to board games that are directly controlled by the players using set rules can add more excitement and strategy options.

7 Conclusion & Future Work

By designing and fabricating four electrochromic displays in the same hexagonal shape of the original Settlers of Catan tiles we added another dynamic elements that allows for more strategic play and tension. The designs of the displays featured simple iconography of the normal resources designs in the game (wool, grain, brick) to not deviate too much from the original game, in addition we also added a new feature (golden chest) to force some new strategies. Our preliminary studies indicate that players prefer using Hybrid Settlers over the original game as it adds more dimensions and randomness to the game. Also, by allowing the players to manually select which dynamic tiles change resource enable them to get more personal in their strategies as they can directly obstruct an opponents game.

For future work we are interested in exploring how more and more modular elements that can be re-arranged on the fly to create new game board layouts. Furthermore, we also want to investigate in more extensive studies how adding these dynamic elements influence the perception of the game and how they affect the strategies used in a game.

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