# DisplayFab: The State of the Art and a Roadmap in the Personal Fabrication of Free-Form Displays Using Active Materials and Additive Manufacturing.

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**Figure 1: The DisplayFab Roadmap: a framework to structure challenges and opportunities for the development of material-centric personal fabrication of displays and by extension interactive devices. DisplayFab is derived from identifying 4 breakpoints where the PersonalFab framework [10] is no longer applicable to the fabrication of displays. We structure a new framework, using these breakpoints to categorise related work and analyse research opportunities and future direction.**

## ABSTRACT

Over recent years, there has been significant research within HCI towards free-form physical interactive devices. However, such devices are not straightforward to design, produce and deploy on demand. Traditional development revolves around iterative prototyping through component-based assembly, limiting device structure and implementation. Material-centric personal display fabrication (DisplayFab) opens the possibility of decentralised, configurable production by low-skill makers. Currently, DisplayFab is severely limited by its embryonic stage of development, the complexity of involved processes and materials, and the challenges around designing interactive structures. We present a development framework to provide a path for future research. DisplayFab has been developed by identifying 4 key breakpoints in the existing “Personal Fabrication” framework: Material and Deposition, Conception and Software, Feedback and Interactivity and Responsible Innovation. We use these breakpoints to form a targeted literature review of relevant work. Doing this we identify 30 challenges that act as roadmap for future research in DisplayFab.



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## KEYWORDS

Display Fabrication; Printed Electronics; Additive Manufacturing; Personal Fabrication; Active Materials; Interactive Devices

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## 1 INTRODUCTION

Leading from Sutherland's inception of "The Ultimate Display" [183], HCI's physical computing research has focused on exploring all varieties of digital interfaces for the expansion of non-traditional free-form interactions with computers. Irregular, non-planar interactive devices, have been introduced as concepts through the seminal contribution of "Tangible Bits" [67, 68] and the foundational "Organic User Interfaces" [62, 195]. Free-form interactive devices have the potential to expand human computer interaction and open new channels through which to interact with the digital world.

However, such interfaces are constrained by the form of the display and there exists no preeminent method to produce high-quality irregularly-shaped physical displays, on demand for custom use. Existing methods to enable free-form interfacing include technologies such as AR [16], VR [36, 112], projected interfaces [12], shape changing interfaces [6, 37, 141, 147, 154, 155] and dynamic manipulations of matter through acoustics [110, 133]. These methods face limitations, such as restricted form factors, occlusion, reliability and reliance on other intermediate devices. Alternatively, makers can build their own displays using component-based techniques, however these are inherently skill dependent and limited in form.

Personal fabrication (PersonalFab) has seen a phenomenal recent expansion in adoption and development, allowing the rapid creation of irregularly shaped objects of all forms through methods such as 3D printing [209]. An increased usage has taken it beyond early adopters into a mainstream set of technologies [9, 148] and makers have been enabled in creating versatile and irregularly-shaped objects domestically, and with form fit-to-purpose. Additive manufacturing has enabled the lowering of barriers to entry with lower required skill levels, as well as more approachable environments and equipment needs through automation, directly through the deposition of homogeneous malleable material. However, current additive manufacturing is largely limited to inactive materials.

**The personal fabrication of addressable displays via the deposition of active display materials**, which we term **DisplayFab**, encompasses the decentralised production of interactive objects, enabling broader human-computer interactions through free-form devices. DisplayFab represents a significant hurdle in the material-centric fabrication of free-form devices. Such devices can be parameterised as input, output and control. Methods for fabricating input structures, typically through capacitive touch, are well explored and converge in process (e.g. [50, 93, 163, 220, 223]). Meanwhile, personal fabrication of control through materials is easily integratable via components without limiting form. However the fabrication of displays and output is diverging in method, challenges and required skill-sets opening a need for unification. Significant recent works have explored material-centric methods for fabricating interactive devices [54, 55, 75, 206, 207, 216]. By harnessing active materials and constructing outputs from base properties, end devices can truly attain a free-form nature, being unconstrained by the conformal forms of regular or even customisable components. In addition, these works build towards the promise of automated, decentralised production of interactive devices unlocking free-form interaction for all.

DisplayFab development is inherently limited by a range of challenges beyond those faced in the personal fabrication of non-active objects. DisplayFab currently exists as a subset of personal fabrication. However, we argue that DisplayFab holds unique limitations on its development that must be addressed beyond the broader area of personal fabrication. We identify these limitations as taking the form of three factors: **1) Early stage of development:** resulting in a divergent array of infrastructure, methods, materials and processes within related work limiting adoption. **2) Complexity** of systems: directly resulting from fabrication processes and materials that are required for material-centric construction of interactive objects. **3) Designing for interaction**: merely designing physical forms is insufficient for fabricated interactive objects. Field-specific knowledge from within HCI needs to be incorporated from the ground up within tools, methods and design process in order to support interactive device fabrication. We put forwards a novel framework as an extension of the existing state of the art personal fabrication framework, that should be seen as a specialised variant specifically for display fabrication. Founded as an adaptation of Baudisch and Mueller's personal fabrication framework [10], we take the constraints to research specific to DisplayFab and argue that DisplayFab must be managed independently to adequately deal with limitations on development. As a result we present the DisplayFab framework, independent of PersonalFab.

We thus contribute a framework for DisplayFab research to accelerate research and development. From the PersonalFab framework [10], we expose four key breakpoints for which DisplayFab diverge: 1) Hardware and materials specific to display fabrication; 2) The Conception and software, that support designing for interaction; 3) Feedback and interactivity with the fabrication process; and 4) the need for Responsible Innovation. We use these breakpoints to review the literature in multiple related fields. Through this we identify 30 challenges that act as roadmap for future research in DisplayFab.

## 2 RELATED WORK

In this section we focus on analyzing visions for free-form interactive devices, as well as frameworks relating to personal fabrication and key areas that can be applied to DisplayFab. We will review work in the area of material-centric DisplayFab in the rest of this paper.

### 2.1 Concepts and vision for free-form displays

Free-form interfaces have appeared through a number of preeminent works. Weiser introduced the concept of ubiquitous computing [205], developed within research through prototyping, leading to interaction beyond GUIs and supporting HCI's interest as a field in prototyping and personal fabrication. In 1982, Schneiderman [172] examined the history of direct manipulation and identified user's desire for "comprehensible, predictable and controllable interfaces". Ishii developed the vision further, through "Tangible Bits" [68] into "Radical Atoms" [67], expanding interaction concepts through irregular shapes to malleable free-form interfaces. Beaudouin-Lafon argues for integration of alternative interfaces in functional, real-world settings [11] which inspires out motivation to use fabrication as a means to enable on-demand interactive device deployment. Alongside, the concepts of Organic User Interfaces were developed with a focus on form and integration within environments [62, 196]. Meanwhile Fitzmaurice *et al.* explore the efficiency benefits to interaction of physical tangible objects in "Graspable UIs" [40, 41]. Recently, Sweeney *et al.* introduce the concept of "displays as a material" [185], developing ideas of treating interfaces as both malleable and formable with a different perspective on the links between display fabrication and material science. Finally, Alexander *et al.* [6] identify and categorise the challenges toward building shape-changing devices. We argue that the overlapping visions within these works can be achieved through the fabrication of physical free-form interactive devices.

### 2.2 Frameworks related to DisplayFab

There are a range of taxonomies, literature reviews and frameworks that explore challenges through which we guide the development of an appropriate roadmap for free-form displays. Displayfab draws on both those which discuss irregularly shaped displays and those which focus on personal fabrication processes. For free-form displays, Brudy *et al.* [19] provide a taxonomy for supporting research in cross-device systems going beyond traditional screens. Predating this work, in 2001, Ullmer *et al.* [194] provided steps towards a framework for Tangible User Interfaces and steps that DisplayFab can build on with regard to bridging the digital-physical divide. Jacob *et al.* provide a framework for reality-based interaction [69], acting as a foundational work towards the interaction benefits of physical devices with form and function that align with use. Roudaut *et al.* [154] provide a framework from shape changing displays and shape resolution within "Morphees", that is extended by Kim *et al.* [88] to applications of everyday forms. Despite the scope of deformable surfaces, DisplayFab can draw on the topographical distinctions and limitations while providing material-centric facilitation for this vision of shape-changing interactive devices. Qamar *et al.* provide an extensive literature review spanning shape changing structures between material science and HCI [147]. Similarly, Nittala *et al.* carry out an inter-disciplinary literature review, exploring epidermal user interfaces [131]. These frameworks provide a broad range of factors relevant to DisplayFab, relying on manufacturing or reconfigurability rather than fabrication. We categorise DisplayFab through fabrication as a way to enable makers to design and produce on-demand interactive devices for bespoke uses and so cast a wider net for fabrication related frameworks.

Willis *et al.* [209] explore interactive fabrication through a series of prototypes, and outline the levels of interaction that can be taken by a user during the fabrication process. Sass *et al.* [159] present a design-fabrication framework specific to large scale prototyping with valuable structural contributions for Dispray. A comprehensive and in-depth analysis of both fabricating and manufacturing irregularly shaped electronics can be found in Rich *et al.'s* review on fabricating electronics on curved surfaces [150]. However, this work looks at both manufacturing and fabrication for a broad range of purposes, leaving scope to explore interactive device personal fabrication in greater depth. Meanwhile, looking at passive personal fabrication but from an impact perspective, Mota *et al.* categorise work on personal fabrication and 3D printing with a focus on future direction, makers themselves and decentralisation, each of which theme inspires sections of the DisplayFab framework [117]. Schmitz *et al.* [162] delineate the space around interacting with personal fabrication's end products in the form of 3D printed objects providing a touch focussed precursor to the fabrication space of interactive devices with output elements requiring further work. Jansen *et al.* bring together work on data visualisation, shape changing displays and tangible UIs to delineate the potential of digitally addressable physical displays for communicating data structures [72]. In "Next steps for Human-Computer Integration" [120], Mueller *et al.* provide a workshop driven overview of challenges to this arena. Meanwhile, Totsuka *et al.* introduce impression based fabrication as a concept in their study proposal [193]. Lastly, Conner *et al.* provide a road map of 3D printing from the perspective of industrial integration [30], providing a pathway for academic-industry collaboration for 3D printing of inactive objects, with transferable frames to interactive device fabrication. While these works partially span core challenges and research opportunities relevant to DisplayFab, they neither address the full extend of these challenges not provide the full picture of what needs to be addressed to effectively breakdown the barriers to DisplayFab's implementation and so motivate the need for a novel framework.

## 2.3 The "PersonalFab" framework

The gold standard framework on personal fabrication was constructed by Baudisch and Mueller in their book "Personal Fabrication" [10]. The authors analyse the state-of-the-art of related research and frame future challenges around personal fabrication. This framework (the "PersonalFab framework") forms a foundation for us to analyse current work and identify challenges for DisplayFab. Therefore, we present this work in depth:

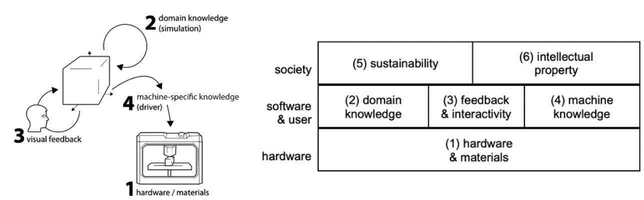


**Figure 2: The PersonalFab framework: (Left) a schematic of the pipeline for personal fabrication highlighting four challenges: (1) hardware/materials, (2) domain knowledge, (3) visual feedback, (4) machine-specific knowledge; (right) the six full challenges with two additional contexts: sustainability and intellectual property (figure from [10], image copyright maintained by owners: Foundation and Trends, Now Publishing.).**

The PersonalFab framework (Figure 2) was built on related work until 2017 and spans the gap between academic research and innovations through methods such as 3D printing and laser cutting within the maker community.It utilises the AD/DA media structure for readying a field for consumers from software adoption and categorises 6 challenges:

(1) **Hardware and material** encompassing the development needed to ensure the fabrication of objects.
(2) **Domain knowledge** covering systems that embody the domain knowledge (e.g. physics simulations).
(3) **Feedback and Interactivity** encompassing systems that allow for synchronous user-machine input.
(4) **Machine Knowledge** encapsulating machine-specific knowledge required of a specific fabrication machine.
(5) **Sustainability**, which includes factors such as device disposal, material sourcing, and energy consumption.
(6) **Intellectual Property**, which covers protection of designs.

These challenges are used to map future work. Within this structure, Baudisch and Mueller additionally cover related work exploring interactive devices fabrication. Examples beyond inactive object fabrication also include 3D printing of electronics [163] and the use of optical and light pipes [18]. However, we identify a disjoin in the nature of research challenges when applying the PersonalFab framework to the fabrication of interactive devices and visual output devices. Stemming from DisplayFab's early stage of development, complexity and inherent interaction design constraints, challenges are disparate, intersecting and ever-changing. For example, the problem space of deposition and active material are codependent and rapidly evolving providing challenges beyond the frame of PersonalFab.

# 3 THE DISPLAYFAB FRAMEWORK

This section is split into three parts. We provide: 1) A dissection of **what the DisplayFab framework is**. 2) An overview of **how this framework was derived**, as breakpoints from the PersonalFab framework. 3) **Our methodology** for inclusion and exclusion criteria.

## 3.1 DisplayFab framework overview

We adapt the PersonalFab framework to encompass material-centric personal fabrication of displays. We highlight 4 key breakage points highlighting challenges within display fabrication (Figure 3). We define a breakpoint as the stage at which DisplayFab challenges resulting from related works are not categorisable within the existing PersonalFab framework as it stands. In practise this takes the form of either one of the PersonalFab categories not appropriately accomodating DisplayFab research limitations and requiring reformulation (breakpoints 2 and 3) or multiple PersonalFab categories that require reformulation and extension to adequately cover DisplayFab problems (breakpoints 1 and 4).The DisplayFab framework provides a structure for development challenges through 4 categories aligning with each breakpoint (Figure 1).

**"Material and Deposition"**, explores the range of active materials usable by a maker, how they are handled and deposited. Limitations and opportunities are separated into three areas: *"Active materials"* covers works and research opportunities relating to active materials, procurement, development and functionality. *"Fabrication hardware"* covers deposition methods, manipulation of materials onto substrates and precision in layering. *"Location and availability"* covers geographical situation of fabrication and access for non-specialists to equipment and spaces.

**"Conception and Software"** covers methods through which a maker can design interactive devices and the use of software to support these processes. Subcategories are delineated as: *"Design support:"* covers challenges regarding designing for interaction integrated design. *"Domain knowledge:"* covers specific information relating to techniques and implementations. And lastly, *"Learning"*, covers the dissemination of specialised knowledge.

**"Feedback and Interactivity"** refers to supporting makers in the process of fabricating devices, through interactive methods and specialised guidance to those involved. The subcategories are structured as: *"Interactive fabrication:"* relating to work supporting iterative and continuous user input within the personal fabrication of inactive objects. We include work that has the scope for development within DisplayFab. *"Testing:"* refering to research on unifying evaluative measures and providing consistant performance evaluations of output devices.

**"Responsible Innovation"** explores the impact of DisplayFab on both people and society as well as the broader impacts of developing these technologies. Challenges fall under: "*Intellectual property:*" covering questions from ownership of materials and devices to control over digital information that can appear anywhere. "*Sustainability:*" covering material sustainability and environmental impact. "*Health and safety:*" looking at mitigation of material hazards, dispersal and hostile display stimulae. Lastly "*Ethical impact on users*" addresses questions of the divides between users and makers, and malicious device use.

## 3.2 Breakages of the PersonalFab framework when applied to DisplayFab

The PersonalFab framework has 4 fundamental breakages when applied specifically to the subset of PersonalFab that is DisplayFab. These 4 breakages become the categories for our DisplayFab roadmap of challenges and limitations within personal display fabrication that we present here.

### 3.2.1 *Breakage 1: Material and Deposition.*

PersonalFab's categories of "machine specific knowledge" (4) and "hardware and material" (1) (Figure 3) overlap when applied to DisplayFab. We identify this as our first breakpoint: "Material and Deposition". Under DisplayFab, there are limited bespoke set-ups for personal fabrication of displays and no commercial domestic setup. Related work largely repurposes craft tools and personal fabrication methods for active materials. We identify the need for a new category encompassing "Material and Deposition", due to:

- A lack of bespoke devices, machine specific knowledge is integrated in material choice and hardware used as well as the domain knowledge of the maker as a result of the relatively early-stage development of DisplayFab.
- DisplayFab having significant inherrent complexity, shown through divergence in recent work use of both hardware and materials, with the use of bespoke equipment and custom active materials being interlinked.

As a result DisplayFab categorises limitations under a broader category: "Material and Deposition" within which challenges to makers surrounding materials, fabrication tools, location and availability can all be structured.

### 3.2.2 *Breakage 2: Conception and Software.*

This breakpoint identifies a single category of the PersonalFab framework that breaks when applied to DisplayFab: "Domain Knowledge (Simulation)" (2). The new Category "Conception and Software" is required for DisplayFab due to:

- Inherrent complexity and the need to design for interactive purposes requiring greater design-related considerations at an earlier stage and by extension a direct integration within fabrication tools and processes. Specifically, empowering makers and end-users with the ability to create displays means endowing them with the capabilities of creating user interfaces and complex designs. Beyond complexity, we also identify the need to support designing for interaction at a fundamental level beyond the challenges provided within the PersonalFab framework.
- The embryonic nature of the field meaning that different domain knowledge considerations must be taken into account focused on expanding specialised understanding of a wide range of different materials and processes rather than propagation of understood and widely used processes as is the case for existing personal fabrication.

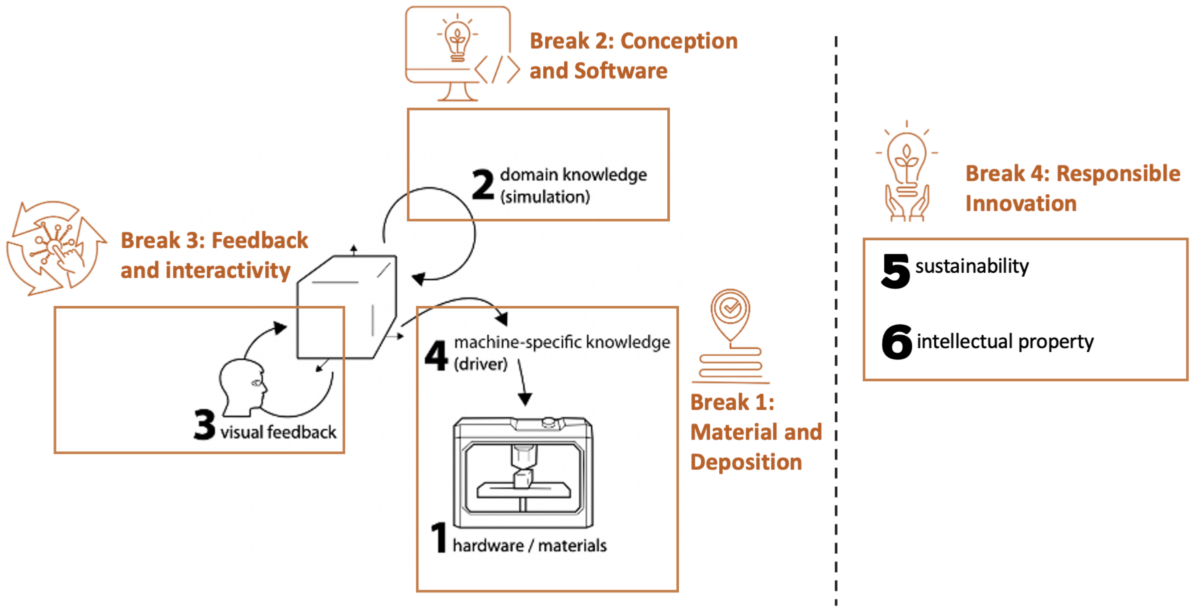


**Figure 3: In applying the PersonalFab framework to Display we found four main breakage points: 1) Material and Deposition; 2) Conception and Software; 3) Feedback and Interactivity and 4) Responsible Innovation. Image adapted from [10], image copyright maintained by owners: Foundation and Trends, Now Publishing [10].**

As such, PersonalFab's "Domain Knowledge" is expanded into "Conception and Software" which include the process through which a maker develop a device, interactive material-specific domain knowledge and the process of learning. While this category maps to Perosnalfab, the requirments and challenges are fundamentall different as a direct result of DisplayFab's complexity and the need to design for interaction. As a result, this category goes beyond PersonalFab's "Domain Knowledge" within the reformed DisplayFab framework.

*3.2.3 Breakage 3: Feedback and Interactivity.* This breakpoint arises from PersonalFab's "Visual feedback" (3), both broadening challenges to include testing and assessment of functional devices and translation of interactive fabrication concepts to DisplayFab. This redefinition and breaking of the previous structure follows as a result of:

- Craft-based and hand-held methods being the norm within DisplayFab leading to a greater overlap with interactive fabrication from PersonalFab but with a different development path due to the lack of bespoke tooling.
- An acknowledgement of the need for both tolerances in failure when fabrication is concerned with functional output and the need for unification in what is acceptable, measurable and of interest when it comes to the output factors of interactive devices.

As a result, "Visual Feedback" is extended to DisplayFab under a new category "Feedback and Interactivity".

*3.2.4 Breakage 4: Responsible Innovation.* Within PersonalFab, "Society" covers Sustainability (5) and Intellectual Property (6) (Figure 2). Our breakpoint both reformulates and extends the category. We identify the importance for research questions into the roles of "Health and Safety" and "Ethical impact on Users" that are not currently formulated but are important. Meanwhile, the roles of "Intellectual property" and "Sustainability" require reformation:

- "Health and Safety" is of greater importance and is less explored within DisplayFab as a result of the intersecting priorities between display performance and fabricatability, resulting in danger to makers.
- The "Ethical Impact on Users" is unique to interactive devices fabrication and categorising limitations and constraints under this banner identifies space within which to explore user-maker dynamics and malicious vs. benign impact, inherent to decentralised interaction.
- Lastly, we propose a re-characterisation of some limitations from PersonalFab within IP and sustainability when applied to DisplayFab. For example DisplayFab has limited files or tools that require IP considerations. Conversely, DisplayFab IP issues revolve around material and equipment use and availability through commercial restriction (e.g. the use of E ink [54]). Within sustainability, the small scale of DisplayFab as a field both shifts the challenges relating to sustainability but also gives rise to an opportunity to shape development with sustainable practices.

As such, PersonalFab's sections Sustainability (5) and Intellectual Property (6) become redefined and expanded under DisplayFab's broader category "Responsible Innovation". This breakpoint extends PersonalFab and uniquely amongst other breakpoints, the challenges are largely commutable to PersonalFab. However, we identify it as a breakpoint in PersonalFab's ability to comprehensively cover the facets of DisplayFab that must be further explored.

## 3.3 Derivation of the DisplayFab framework

The DisplayFab framework was developed through a targeted literature review of papers specifically contributing work towards the personal fabrication of displays through material-centric approaches. This review returned a core set of 20 key papers. These papers were analysed in depth and from them we drew key themes, challenges and opportunities relating to the adoption, development and implementation of DisplayFab processes. We then expanded on these research directions by engaging with a broader set of related works accessed through the core papers of the literature review, or subsequent themes that arose. To adequately carry out a targeted review we first clearly define the scope of DisplayFab:

*3.3.1 Displays as a facet of interactive devices.* Interactive devices can be broken down into input, output and control with input predominantly being touch based whereas output is visual. We identify that for the fabrication of interactive devices, the constraints related to *input* methods are aligning and amenable to resolution under the PersonalFab framework. Material fabrication of *Control mechanisms* is fundamentally limited by material constraints on producing stable transistors or power supplies. We note that due to software configurability and microcontroller technology there is little need for this development as the form of control is often separable from the interactive device's form itself. In stark contrast, research works and developments in the realm of material-centric personal fabrication for *displays* are diverging and rapidly developing. Consequently, we argue that the challenges and limitations linked to this aspect are the greatest limitation on the personal fabrication of free-form interactive devices and hence the focus of this roadmap. By "solving" display fabrication, we aspire to unlock the fabrication of free-form interactive devices as a whole.

*3.3.2 DisplayFab formal definition.* We formally define DisplayFab, such that we can use this definition to sort this research within the related work and set limitations on the scope of this research. So what does this definition mean?

First, DisplayFab is defined as falling within *(1) personal fabrication.* In this context, personal fabrication refers to decentralised, production of objects with a focus on usability of methods and materials by non-specialists. Specifically, this excludes large-scale display manufacturing.

Second, Displays that are *(2) electronically addressable* to convey digital information. This includes use of output mediums such as colour change or light emittance as long as their stimulus can be controlled digitally, even if not directly (e.g. thermochromic system with a Peltier module) but excludes non-electrical activation (e.g. a thermochromic mug). In this context, Display (as used in the term 7-segment display) is defined to mean a visual non-kinetic output that can be directly or indirectly electronically addressed, specifically to convey information to a user. We constrain DisplayFab to visual output based on its predominance in current interactive device technology, however we leave other modalities for future expansion of the framework.

Third is the *(3) deposition of active materials.* Within this delineation we define DisplayFab as taking one of the key features of additive manufacturing: The use of malleable homogeneous materials (such as 3D printing filaments and resins) that can be transmuted through cooling, curing or drying to create objects from scratch. Active display materials refer to materials that are responsive to stimulae to either change colour or emit light, specifically those that enable the visual conveyance of digital information.

*3.3.3 Derivation methodology:* We the methodology of our derivation of DisplayFab, starting with the targeted literature review. We use the formal definition of DisplayFab to precisely define the scope of our framework. We set inclusion criteria, carried out a precise search and used this as the basis for the DisplayFab framework. Our inclusion criteria are directly drawn from the DisplayFab definition given above: that the core papers could be included if work provided contributions under 1) personal fabrication, 2) electronically addressable output, 3) manipulation of active materials for free-form interactive device creation. To maximise our chances of including relevant works, we searched under categories of material key words (e.g. electroluminescent), deposition methods (e.g. screen printing) and general personal fabrication terms (e.g. personal fabrication of interactive devices) using both the ACM digital library search engine and Google Scholar. We initially scoped works using broad search terms and identified that likely as a result of the early stage of development of this field there are relatively few pieces of work directly on DisplayFab. As a result, a systematic literature review would have therefore not yielded a significant quantity of works under the inclusion criteria determined by such an embryonic subfield as DisplayFab and as such we opted to carryout a more irregular targeted review. As the DisplayFab framework is a forward facing roadmap, primarily focused on future research challenges, we justify this decision as a constructive step in building DisplayFab. The initial review returned 20 papers listed here, categorised here by material: electrolumienscent [49, 90, 134, 207, 208], electrochromic [15, 25, 47, 74, 75, 126, 128], photochromic [82, 145, 206], thermochromic [84, 139, 216] and electrophoretic [54].

Following the identification of our core set of papers we carried out a series of structured discussions between the authors to identify research challenges, opportunities and contributions both within existing works and for future work. We carried out weekly discussions between authors over the course of 12 months. We initially drew challenges from limitations sections and further inference from the core 20 papers. We added our own challenges that had arisen in our first hand experience of DisplayFab research. We worked towards a comprehensive map of challenges by asking the questions of "What was the process?", "Where would it take place?", "How would desired outcomes be achieved?", and "Who is any given DisplayFab method for?" (see Annex for further detail). We iterated through groupings of challenges into broader themes, using the criteria of whether these could 1) fully encompass related work 2) act as a frame for further opportunities. We used these to create affinity diagrams through which we condensed core challenges and how they interplay with each other.

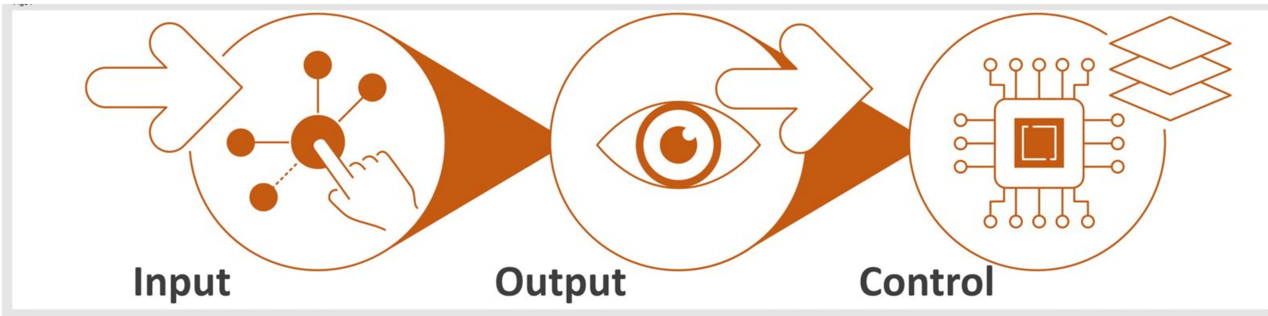


**Figure 4: Our framing of the considerations needed for the formation of an interactive device: 1) input capability, 2) output capability and 3) control. We posit that in the context of fabricating interactive objects, the challenges and limitations around input are converging and addressable under the PersonalFab framework, while there is limited scope to addressing solving control. In contrast, work on material-centric personal fabrication of output capabilities is diverging and the associated challenges and limitations are the area most needed to be addressed. DisplayFab specifically addresses research working towards the personal fabrication of free-form visual output.**

In the process of developing the themes and research directions through affinity diagrams and discussion, we iteratively expanded the scope of relevant works, drawing in other works based on themes and challenges that arose. We used the references of the key papers and the papers that cited them (using Google Scholar's "cited by") to build this body of related work. These works are presented within the framework below. However, for clarity we also categorised these works as contributing towards one or more of the following topic areas that are adjacent to DisplayFab:

- Research into *interactive fabrication* as a means to enable DisplayFab.
- *Component-based* display fabrication.
- *Active materials* research beyond HCI, within material sciences.
- Personal *fabrication of inputs* and sensors only.
- *Interactive devices* research covering designing for interactivity.
- *Non-academic sources* of information such as patents, commercial suppliers and independent practitioners.

It was only after building these themes and this larger body of work that we integrated the challenges and limitations within the existing PersonalFab framework which led to the identification of the 4 breakpoints where PersonalFab does not adequately encompass research around DisplayFab. We identified that the challenges mapped within these affinity diagrams could act as a framework but we identified that there was overlap with the PersonalFab framework. We attempted to categorise the challenges identified with the PersonalFab structure, however in doing so we identified 4 key areas of divergence in challenges which become the 4 breakpoints in this paper. Returning to pertinent challenges unique to DisplayFab, we comprehensively mapped these to the 4 breakpoints and structured a roadmap around 30 key challenges.

In the following four sections we present the four component categories of the DisplayFab framework, populated with relevant related work and use it to outline key research challenges and opportunities. We introduce the key DisplayFab papers to date in the materials section, and integrate the broader body of related work (that have contributions under the above 6 categories) within the following sections. These works both help shape the scope of existing DisplayFab work and the challenges that provide a roadmap to future research.

## 4 CATEGORY 1: MATERIAL AND DEPOSITION

### 4.1 Active materials

In personal fabrication of inactive objects, methods and materials diverged early-on as different techniques were tried out. They re-converged following adoption and commercialisation. As a subset of personal fabrication, DisplayFab is at such an early stage that the works in this field are significantly diverging in methods, materials and goals.

*4.1.1 Context and related work.* The preeminent material choices for DisplayFab are electrically addressable active materials: electroluminescent (EL) and electrochromic (EC). EL and EC are both controlled through paired electrodes enabling an inbuilt structure for capacitive touch sensing. EL emits light under stimulation whereas EC changes colour or opacity. Thermochromic (TC), photochromic (PC) or electrophoretic (E ink) also hold alternative potential (Figure 6).

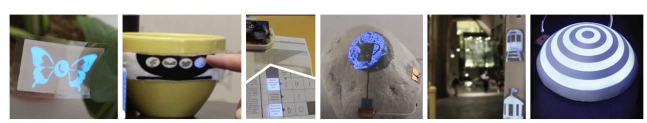

**Figure 5: Related work of personal fabrication of displays using electroluminescent material: PrintScreen [134], Stretchis [208], Illumipaper [90], Objectskin [49], Sprayable User Interfaces [207] and Protospray [55]. All images copyright maintained by original owners: ACM**

*Electroluminescent:* PrintScreen is one of the earliest implementations of DisplayFab within HCI (Figure 5). Olberding *et al.* [134] introduced methods accessible to non-specialists to manipulate EL

| | | Electroluminescent | Electrochromic | Photochromic | Thermochromic | Electrophoretic |
|---|---|---|---|---|---|---|
| End-device properties | *Refresh rate* | ●●●●● | ●●●○○ | ●●●○○ | ●○○○○ | ●●●●○ |
| | *Colour variety* | ●●●○○ | ●●○○○ | ●●●●● | ●●●○○ | ●●●○○ |
| | *Flexibility* | ●●●●○ | ●●●○○ | ●●●●○ | ●●●●● | ●●●○○ |
| | *Durability* | ●●○○○ | ●●●●○ | ●●●●○ | ●●●●● | ●●●○○ |
| | *Ease of control* | ●●●●● | ●●●●● | ●●○○○ | ●○○○○ | ●●●●● |
| Fabrication Process | *Material friendliness* | ●●●○○ | ●●○○○ | ●●●●● | ●○○○○ | ●●●●○ |
| | *Device failure risk* | ●●○○○ | ●●●○○ | ●●●○○ | ●●●●○ | ●●●●○ |
| | *Low material cost* | ●●●●○ | ●●●●● | ●○○○○ | ●●○○○ | ●●●●● |
| | *Low control cost* | ●○○○○ | ●●●●● | ●●●○○ | ●●●●○ | ●●●●● |

**Figure 6: An overview of active material choices with regards to utility, on a scale of 1-5. We developed this overview to support appropriate selection for future projects based on related work and our own experience using active materials.**

materials to produce segmented and pixelated display elements. In "Stetchis", Wessely *et al.* [208], expand screen printing techniques through use of PDMA to enable EL display fabrication for stretchable surfaces. EL's malleable and robust properties [56, 95, 97, 173] have allowed for irregular surface layering such as in Sprayable User Interfaces [207], ProtoSpray [55] or ObjectSkin [49]. Groeger *et al.* use hydroprinting to layer active materials on a non-comformal plane. Wessely *et al.* use spraying as a means to deposit EL material to create insitu interfaces that can be additively expanded. Lastly, Hanton *et al.* [55] integrate domestic 3D printing and EL spraying to enable makers to rapidly produce free-form interactive devices. Of particular importance to DisplayFab is the handling of active materials. Klamka *et al.* use fabricated EL displays for the context of interactive paper in "Illumipaper" [90]. Meanwhile, EL cells are used in Skinmarks [204] on irregular surfaces but are created on a flat topology via screen printing, before application via transfer paper and only conformal to gently curved surfaces. Within these works, procurement of El material was possible commercially [106, 107, 119] and there also exist adjacent non-academic work using these materials [64, 96]. Publications beyond HCI show the feasibility of printing and spraying EL materials. Bharathan *et al.* [14] work on EL inkjet printing, Sandstrom *et al.* [158] introduce "spray-sintering" for EL on irregular surfaces and Asadpoordavish *et al.* [7] extend the use of spraying. Both Aleksandrova *et al.* [5] and Fujita *et al.* [46] look at optimising electrical properties.

**Figure 7: Research projects exploring electrochromic personally fabricated displays: Chromabot [15], Transprint [75], EC running shoe [128], Cleanleaf [25], Always with me [74]. All images copyright maintained by original owners: ACM**

*Electrochromic:* Electrochromic displays have the properties of being non-light emissive, free-form, flexible, transparent, energy efficient and low contrast with ease in prototyping [126] (Figure 6). The Decochrom project [32] has thoroughly explored electrochromic materials. In Transprint, Jensen *et al.* [75] underpin EC's technical strengths for display fabrication. Moreira *et al.* [115] provide a detailed overview of EC's potential within inkjet printing for use in display fabrication with further technical contributions towards optimising EC [114, 115]. Meanwhile, workshops carried out by Löchtefeld *et al.* [103, 104], Muller *et al.* [127] and Jensen *et al.* [77] have propagated EC fabrication. Within fabrication, (Figure 7). Vitaboot [76] an EC display within footwear while Kololuoma *et al.* [94] look at processes for producing EC displays. In "Linn dress" [73], Jarusriboonchai *et al.* explore personally fabricated EC's use in clothing while Genc *et al.* introduce the "decolive" jacket to support social interaction [48]. Chromabot [15] introduces a fabricated soft-robotic appendage with embedded EC material. Meanwhile, EC design spaces are explored by Colley *et al.* [26] (Figure 7). Explorations of vehicular interior applications are made in [27], while Jensen *et al.* [81] integrate small scale fabricated devices into tabletop gameplay. In table [25], Colley *et al.* use EC technology for epidemiological mitigation. Hakkila [52, 53] investigates the usage space around the concept of an interactive gravestone, whilst Muller *et al.* integrate EC within a running shoe [128]. Other work explores ambient conveyance [126] (Figure 8). Genc *et al.* promote wearable EC fabricated face masks to support occluded facial expression [47]. Li, Jarusriboonchai *et al.* develop structures for intimate communication [74, 99]. Jensen *et al.* innovate information conveyance via EC material using digitally addressable shadows [78, 80] as a new medium of display based on EC fabricated devices. Beyond Decochrom, Junnarkar *et al.* explore the "slowness" property of EC [83].

*Photochromic, thermochromic and E ink:* Other display materials are less heavily researched due to material limitations. PC is used in DisplayFab typically in a single layer without the need for a multi-layered structure [82], updated via an external projector or laser. This allows for complex information to be displayed without the limitations of fixed electrodes, and its bistable nature allows objects to retain their new visual texture (Figure 9). On the other hand, the updating process is significantly slower than EL and comparable to EC (up to a minute [75]). Applications developed using PC material cannot be as easily simulated using component-based

**Figure 8: Research projects exploring both electrochromic and electrophoretic personally fabricated displays for information conveyance. Always with me [74], Ambient display design space [126] and EC facemask [47] as well as an exploration of E ink fabrication within FabricatINK [54]. All images copyright maintained by original owners: ACM**

fabrication providing unique applications. Photochromic material was initially used within HCI in Hashida *et al.*'s "PhotoChromic Canvas" [57], published alongside "PhotoChromic sculpture" [58]. More recently, in ColorMod [145] (Figure 9), Punpongsanon *et al.* introduce reprogrammable photochromic free-form objects using 3D printing. Photochromeleon [82] develops full colour configurability using blended PC inks, while ChromoUpdate [206] improves display properties such as refresh time. Qamar *et al.* explore integrating photochromic dyes within resin printing [146] while Zhu *et al.* [226] explore novel updating mechanisms and Frisk *et al.* [45] extend the PC design space to nail displays.

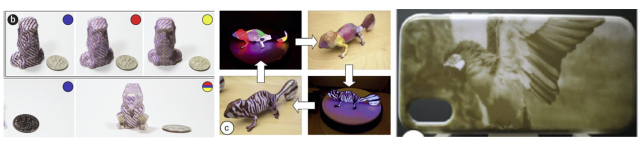

**Figure 9: Photochromic personally fabricated displays related work: Colourmod [145], PhotoChromeleon [82], ChromoUpdate [206]. All images copyright maintained by original owners: ACM**

TC applications use inbuilt Peltier heating elements or Joule heating (for example in TempTouch [138]) to change the colour of a single layer of ink (Figure 10). Thermotion extends TC to provide free form via 3D printed heat channels that provide rapid hydrothermic regulation compensating for a limitations of TC material - slow refresh times [216]. Peiris *et al.* introduce a range of designs and use cases activated through Peltier modules within Ambikraf [139].

**Figure 10: Examples of thermochromic personally fabricated displays related work: Ambikraf [138], Electronic origami [84] and Thermotion [216]. All images copyright maintained by original owners: ACM**

In Electronic Origami [84], thermochromic paper is explored through foldable TC structures, and appliations further developed HeartMe [177] and ChromoSkin [87]. Cho *et al.* [24] explore the playfulness and user-friendly nature of TC materials, while other works look at constructable components such as thermochromic thread [13, 85], with fabrication processes relating to the material-premise of DisplayFab.

#### 4.1.2 Challenges and opportunities.

*Challenge 1: Procurement of materials.* Active materials can be challenging to procure forcing makers to mix, maintain and develop their own materials (e.g. PhotoChromeleon [82], Chromoupdate [206]) or reappropriate materials from other sources (e.g. FabricatINK [54]). This acts as a barrier to use. Both EL and EC are commercially available [106, 215]. However these can be prohibitively expensive and complex to use, highlighting the reliance on economic forces of technological development and adoption even within a non-commercial structure such as decentralised fabrication. Future work must be done both independently and in conjunction with industry to develop more accessible commercially available material products as well as focusing on inter-compatibility and improving dissemination.

*Challenge 2: Diversification of materials.* Uses of active material are defined by their properties and determine specific application scenarios. combined material structures could reduce this limitation following the example of Wang *et al.* [201]. However, existing works do not comprehensively cover all potential depositable materials or combinations thereof. We propose further exploration into new material types and applications. To facilitate this we provide a list of uncommon display materials with sources that we assess to have some potential within personal fabrication if they can be appropriately procured and investigated:

- E ink/microcapsule [28, 60, 70, 71].
- Gyricon/Janus [31, 129, 130, 171].
- Electrowetting [22, 59, 153, 170] and Electrolysis ion [65].
- Interferometric modulator display [17, 20] and related structural colour work [86, 222].
- Printable quantum dot Light Emitting Diodes (QLEDs) [213, 214].

Materials that are explored within HCI related works and in domestic or hackspace lab settings are by necessity forgiving with high thresholds for inconsistencies in thickness. Within exploration into different materials this must be of key consideration alongside robustness, linking directly to capabilities of deposition tools. We also identify the scope to explore active materials with unconventional properties such as deformability, self-healing, biodegradability and more. By approaching the free-form device problem from a material-centric angle, DisplayFab is the platform through which such properties can be put at the core of interactive devices.

*Challenge 3: Device Performance.* Key to material choice and convergence within DisplayFab methods are not only isolated material properties but combined device performance. Personal fabrication of displays introduces structural variables, accurate assessment of materials and optimisation of structural integrities as non-trivial variables for consideration. Robustness, effective information conveyance, fabricatability, energy use, change over time and usability properties all form a complex problem of how to effectively compare performance.

## 4.2 Fabrication hardware

*4.2.1 Context and related work.* Display fabrication methods within existing work are as divergent as active materials. Fabrication processes that are used in related work span screen printing, inkjet printing, spraying, hydroprinting and brush-painting. Kaihou *et al.* use direct painting of TC paint on folded surfaces [84]. Olberding *et al.* [134] use screen printing and inkjet printing. Groeger *et al.* introduce the use of hydroprinting for EL devices [49]. In Stretchis, Wessely *et al.* [208] expand screen printing techniques, while in Sprayable User Interfaces [207] spraying is used to create a fabrication pipeline. Similarly, Jin *et al.* use spraying in PhotoChromleon [82] for applying PC material. Jensen *et al.* developed a two axis automatic deposition device for EC materials [79]. Hanton *et al.* [55] introduce a combined additive manufacturing approach for free-form EL displays through 3D printing and spraying. Meanwhile Child *et al.*[23] implement ultrasound to manipulate atomised PEDOT:PSS in the formation of EL displays. Many of these processes are only available to specialists in labs or specialist hackspaces with niche equipment and tools (Figure 11).

**Figure 11: Fabrication methods for active material deposition and layering related work: Paintbrush and craft-based methods (shown here is conductive BareConductive paint [29]) used in display fabrication - Kaihou *et al.* use this process for TC materials [84], screen printing [75], inkjet printing [134], hydrodipping [82] and spraying [207]. All images copyright maintained by original owners: ACM**

Within related work, most DisplayFab output devices are realised through segmented display types [90, 134]. Within DisplayFab work, configurability to allow for any output is typically included within the fabrication stage. Currently, inability to produce high resolution output means that information determination has to be determined on fabrication facilitated by the rapidity of device production. This is limiting the potential applications. The opportunity for *dual configurability* goes hand-in-hand with solving device resolution, allowing form to be determined on creation and configurable digital information on use. We look at 1) production methods beyond personal fabrication and the extent to which they can be applied in a domestic setting and 2) personal fabrication methods for creating input-only devices and the context in which methods can be applied to DisplayFab in absence of research yet being developed in this area.

*Fabrication methods:* Non-HCI works contribute key findings and in some cases provide the opportunity for direct translation to a domestic setting. In "Spraying Light", Sandstrom *et al.* look at the spraying of a three tiered EL structure onto irregular surfaces. Fujita *et al.* [46] explore spray depositon of EL materials within a non-domestic non-display focused settings. Lewis *et al.* [98] contribute an overview of 3D printed electronics meanwhile, Abdellah *et al.* provide a characterisation of sprayable photoactive layers. On the technical spraying of active materials Zhang *et al.* [219] look at airbrush spraying and masking to produce high accuracy conductive traces for ubiquitous printed electronics. Falco *et al.* [39] explore spraying of active materials further, specifically looking at spray deposition on 3D printed surfaces. These works provide engineering contributions appropriate to DisplayFab.

*Fabrication of touch sensitive devices:* We identify both materials and methods with potential for integration with display materials, through related work on touch sensing. Typical materials are metals including silver, copper or carbon mixtures [29, 144]. These can be used as the base electrode for display materials such as EL or EC inks [55]. Schmitz *et al.* present Capricate [163], providing rapid prototyping via 3D printed conductive traces. Wang *et al.* develop bespoke machinery in "Xprint" to enable smart material liquid printing [199]. Zhang *et al.* explore deposition at larger scale with Wall++ [220] to create a wall sized sensing array using nickle based paints. Wang *et al.* explore augmentative conductive traces to support touch and the addition of components to post fabrication structures [200]. Meanwhile in LightTrace, Ta *et al.* use deposition of conductive ink to integrate components within circuits [186]. Pourjafarian *et al.* develop an augmented tool to support fabrication of on-skin conductive interfaces [142]. CurveBoards, represents the development of bespoke breadboards [224]. Within "Thermoformed Circuit Boards", Hong *et al.* [63] look at fabrication of prototyping tools for partially deformable circuit. Klamka *et al.* develop a new method for the deposition of conductive traces using an ironing layering device, which although not material based, integrates automated deposition of conductive materials [91]. Pourjafarian *et al.* present "Print-A-Sketch" [143] to allow for small scale automatic deposition of conductive traces.

Additionally, works towards automated fabrication of non-digitally alterable objects provide contributions towards foundational work for DisplayFab. Zeng *et al.*'s "Lenticular Objects" [217] stretch the boundaries of what domestic 3D printing is using polyjet Stratasys printer [181]. Yan *et al.* show the creation of 3D printable free-form display objects using structured chambers rather than active materials [212]. Further examples intersect with key DisplayFab work such as Zhang *et al.*'s Computational Hydrographic Printing [221] or Panozzo's work [137] on hydroprinting's potential for computational input with a clear link to methods used in Objectskin [49].

*4.2.2 Challenges and opportunities.*

*Challenge 4: How to improve resolution and fidelity.* One of the most significant limitations to widespread implementation of DisplayFab methods is how to improve the resolution and fidelity of addressable segments and pixels within displays. Given a restriction to domestic or hackspace methods this presents a significant challenge, limiting use of more complex machines [136]. Works on the deposition of conductive traces provide key opportunities for different deposition methods through which fidelity can be improved. We suggest two approaches to this, re-appropriation of existing fabrication tools and development of bespoke fabrication methods. Typically work within personal fabrication has focused on the former (e.g. Olberding *et al.*'s use of screenprinting [134], Wessely *et al.*'s use of an airbrush [207], Hanton *et al.*'s use of domestic 3D printing [55]). We also highlight the benefits of integrating fabricated input functionalities with output both from unification of materials and simplicity of structure, with EL and E ink works broadly following this route and EC, PC and TC deviating.

*Challenge 5: Topographically free-form shapes.* Many related works propose methods for fabricating displays on irregular surfaces either directly [49] or via simulated irregular surfaces using segments and component pieces [74]. These works are typically limited to single display structures, with curves or planes that bend within a single angle through folded or bendable structures.

In addition, future DisplayFab work must address display properties such as display malleability [154] through bendability, foldability and rearrangement. Integration with existing materials [135] must be considered through further research with fabrication methods addressed in conjunction with material investigations. As a step towards free-from devices, further work is required for the identification of where technologically immutable boundaries exist and what is constrained by current development and access.

*Challenge 6: Scaling up of fabrication production.* Existing DisplayFab methods are appropriate for prototyping and production of small quantities of units. Mass manufacture of devices is ill-suited to the current related work. However, as seen within 3D printing there is a middle ground of production of smaller quantities [61]. Craft-based fabrication methods do not scale well and are labour intensive, meanwhile manufacturing pipelines are not applicable. Using lessons learnt from 3D printing, an impactful research direction exists in conjunction with developing bespoke fabrication systems for both custom one-off output but also easy small-scale replication of such devices. We suggest a focus on automation of process and the development of bespoke rather than re-appropriated fabrication tools for DisplayFab to enable domestic production of multiple bespoke interactive devices.

## 4.3 Location and availability

*4.3.1 Context and related work.* Through FDM 3D printing, personal fabrication has a location agnosticism, where printers can be set-up and used wherever. However, other PersonalFab methods, such as subtractive methods (e.g. milling and laser cutting with large machinery) and SLA printers (requiring specific temperatures and extraction) having greater positional constraints on them. All these methods are however restricted to subsets of users within society [116, 211], by location but also broader factors such as access and price. Although there is limited work directly on this area, we suggest using the early-stage nature of DisplayFab to address the same constrains under development.

Key exploration of location-based fabrication considerations is Wessely *et al.*'s work on "Sprayable User Interfaces" [207], investigating sprayable EL materials and their portability. This work takes advantage of spray deposition to allow for interactive surfaces of almost limitless size and fabrication of augmentative surfaces in situ. This is why we need to distinguish between *artefacts and augmentative surfaces.* Artefact creation is the production of objects that can be carried out away from the location of final deployment (such as examples from PrintScreen [134]) while creating augmentative surfaces involves attaching, depositing or integrating interactive features on or into an existing partially or fully immobile setup. Key differentiation applied to output devices defines whether fabricated devices must be produced outside of specialised area and therefore the complications that go along [188].

We use the term availability to refer to access by non-specialists and ability for people to engage with tools and materials. Lochtefeld *et al.* [103, 104] work looked into this issue by developing accessible EC workshops to propagate safe usable DisplayFab methods. Adjacently within PersonalFab, work lights the way for DisplayFab and we raise the question of the extent to which DisplayFab should aim for *fully domestic fabrication.* This raises the question of whether DisplayFab is intended for all through development of domestic practices, or instead a non-specialist, but still not fully comprehensive audience, through use in makerlabs and hackspaces.

*4.3.2 Challenges and opportunities.*

*Challenge 7: Access to processes for a non-specialists.* For true democratisation of processes, access to tools, materials, technology and workshop spaces must be a foremost consideration. We suggest further work into a hierarchy of factors that can determine availability and access to equipment and by extension the democratisation of DisplayFab, building on PersonalFab work such as that of Guo *et al.* [51]. We must also address more recent works that perform fabrication methods in-situ where end displays are to be located.

*Challenge 8: Portability of systems.* Roumen *et al.* explore portable fabrication [156], referring to both mobile fabrication [157] tools as well as software and structure that can be integrated into varying systems in a straightforward manner. This challenge is extended to DisplayFab in both contexts and opens the scope for a range of future research as well as being directly linked to health and safety considerations within responsible practices. Direct integration of open source practices and user-focused design go a long way to supporting portable DisplayFab. However, ongoing research has the challenge of developing solutions to both aspects of portability as DisplayFab itself develops.

*Challenge 9: Control, stimulus and electrode attachment.* In tandem with research into DisplayFab, developing increasingly complex outputs, expansion of appropriate bespoke control structures must also be carried out. In Illumipaper [90], Klamka *et al.* develop an EL driver as a research platform, laying the groundwork for such further development. This work, and further developments on it, represent the opportunity for bespoke control systems that can support research as well as future outputs. Other directions include the custom development of specific control structures such as integrated fabricated Peltier modules [139] of projection set-ups [82] that mitigate occlusion.

# 5 CATEGORY 2: CONCEPTION AND SOFTWARE

## 5.1 Design support

Designing displays or objects with displays, means designing systems to interface between both the digital and physical worlds reliably, predictably and usably. We require tools (software) that include knowledge disciplines that deal with the design, simulation and manipulation of physical shapes, active materials and different control structures.

5.1.1 *Context and related work:* Within prominent DisplayFab works, different approaches are taken to designing, both regarding support of design for interaction but also supporting design via specific fabrication methods (Figure 12). In PrintScreen [134], the design of the circuits that form the basis layer of the display are drawn using a standard 2D vector graphics editor, also seen in Stretchis [208] and ObjectSkin [49]. Each segment or pixel can be done by using traditional application's tools for creating forms. This is similar with other related work such as . These design tools are similar to how designing a file for a laser cutter works or a 3D printer's CAD and slicer pipeline within personal fabrication. These steps require the understanding of a particular pipeline and the expertise of the person who is fabricating the displays.

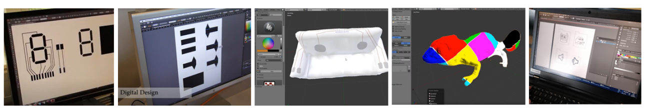

**Figure 12: Bespoke computer aided design (CAD) structures developed for various DisplayFab materials: PrintScreen [134], Stretchis [208], Sprayable User Interfaces [207], PhotoChromeleon [82] and DecoChrom [105]. All images copyright maintained by original owners: ACM**

Sprayable User Interfaces [207] present a detailed design tool to support EL fabrication (Figure 12). ColorMod [145] relies on a PC ink and the authors propose a 3D design tool in order to voxelize a 3D object so as to determine which voxels lay on the outside of the shape and need to be printed with photochromic material. The design tool subsequently connects directly to the 3D printer to print with different material. Meanwhile Protospray [55] and Thermotion [216] integrate existing 3D printing design processes directly, circumventing the need for completely new development.

PersonalFab's *integrated design* has direct translatability to DisplayFab. In OpenFab [197], Vidimče *et al.* develop a pipeline aimed at multimaterial fabrication decoupling material from geometry. In ModelCraft [174], Song *et al.* look at iterating on physical fabricated models through annotations and incorporating them in output objects automatically. In CopyCAD [42], Follmer *et al.* build on this idea of blending physical and digital in the process of design by developing a system that takes physical objects and adapts them to virtual renders that can be edited and remade into physical objects. Carter *et al.* explore designing for interaction through prototyping, focussing on user experience and agency [21].Mueller *et al.* develop Constructable [123], a means to design in real time as fabrication is carried out using an automated system (a laser cutter). Zoran *et al.* introduce FreeD [227], digitalising craft based sculpting. Sethapakdi *et al.* introduce Fabricaide which "interleaves" fabrication and design [169]. These systems lay the foundations for integrated design and bespoke tools tailored to DisplayFab.

5.1.2 *Challenges and opportunities.*

*Challenge 10: What does DisplayFab design support look like?* The current body of related work for DisplayFab only partially addresses how to design the forms of displays and where to place them, beyond enabling the methods of producing them. We draw inspiration from works such as Design-to-Fabricate [161] and modeling-free fabrication [179] which mitigate the use of complex design processes to facilitate adoption. Other work specifically relates to the design of user interfaces for non-rectangular displays with the potential to be integrated within DisplayFab. Serrano *et al.* [167, 168] studied how to generate generic guidelines for non-rectangular displays looking at text mapping, the effect of reading performance and visual layouts leading to design guidelines to reshape content. This research highlights the need for development of design practises. Specifically, there is limited research on how to design displays of arbitrary shape on a personal fabrication level. This is in itself a challenge given the high-dimentionality of possible design spaces that DisplayFab promises.

*Challenge 11: How do we design bespoke tools?* Building on the need to embed design within tools and processes, a natural challenge and research opportunity arises around how such tools are developed. We pose the question: What is the nature of the tools needed and what are the design processes needed to produce appropriate fabrication methods? With DisplayFab, the virtual spaces and necessary structures are less clear cut than PersonalFab as a result of increasing complexity and the split between artefact creation and augmentative surfaces. We highlight personal fabrication's focus on reliability and replicability. This occurs within the context of scientific process but also within fabrication itself where accurate replicability of objects is fundamental. Specifically, embedding knowledge such as electrical, optical or chemical material properties.

*Challenge 12: Prototyping of DisplayFab structures.* Integrating custom prototyping into the DisplayFab process holds significant research opportunity. VirtualComponent [89] explores the prototyping of electronics using mixed reality. Low resolution display alternatives have been developed. For example, Graffiti Fur [182], which uses shading properties of fur change as the fibers are raised or flattened to render images. Sweepscreen [118] similarly uses magnetophoretic surfaces and a device with a row of electromagnets. Lindlbauer *et al.* [101] create appearance changing devices by laser cutting sheets of polymer-dispersed liquid crystal (PDLC) switchable diffuser. Within PersonalFab, low fidelity prototyping such as Wireprint [122] and FaBrickation [124] explore rapid prototyping output. Within "DisplayObjects" [4], Akaoka *et al.* explore designing for interaction through rapid prototyping. Although, DisplayFab can be partially seen as a prototyping tool, we highlight the limitations in this perspective due to its inherent complexity and the suitability of component based methods for prototyping interactive devices [38]. Development of means to rapidly prototype DisplayFab designs would open up appropriate iterative design processes for DisplayFab itself.

## 5.2 Domain knowledge

5.2.1 *Context and related work.* DisplayFab domain knowledge has two key facets: experimentation and the propagation of information to makers. As a whole, DisplayFab core works within HCI and in adjacent fields contribute to expanding domain knowledge, however there is limited work on propagating this information to a wider maker community.

As an proof of concept, we return to the PersonalFab framework [9], notably the adjacent "FabPub" website that covers personal fabrication research projects, encompassing key elements of research into PersonalFab [121]. This ongoing project categorises academics work in an accessible manner, similar to other information-focused platforms such as Haptipedia [165, 166]. Current information is also available to makers through supplier and manufacture-based sources [106, 215] or hobbyist-based platforms [64, 96]. However, centralisation of information from commercial sources has its liabilities to future research. In particular, research endeavours are at the mercy of transparency, accessibility, reliability and rigour as a platform for future work and this leads to challenges around domain knowledge.

#### 5.2.2 Challenges and opportunities.

*Challenge 13: Unification of domain knowledge.* DisplayFab's inherrent complexity requires significant domain knowledge. There are currently limitations as a result of dispersed research amongst academia, industry, hobbyists and artists. The format of this information is disparate and limited in accessibility. There are thus pportunities to develop these liaisons further with HCI. This applies both to DisplayFab as a field and researchers but also as individuals and choosing appropriate materials for appropriate applications and research. An example of this is the datasheets for EL materials [106], which suggest deposition via spray gun with the safety measures of use in a ventilated area. In the context of PersonalFab, work uses these same materials but with a reappropriated airbrush and different, more extensive safety constraints befitting domestic use [207]. A research opportunity exists in extending understanding of such newly developed processes and universalising how this information is propagated.

*Challenge 14: Further material exploration.* DisplayFab domain knowledge to date centers on materials, but the interplay between material information and deposition methods, handling, and processes go beyond just understanding material properties and into hollistic understanding of display fabrication processes. Isolated evaluative research into behaviours must be taken further into compound evaluation to understand and compare active material structures within DisplayFab. This is especially true across different disciplines. As an example, luminosity is often used as a metric for visual output, however there are limited DisplayFab use cases that would benefit from minor changes in luminosity and rather behaviour relating to information conveyance should be addressed through user-centric methods.

### 5.3 Learning

*5.3.1 Context and related work.* Beyond access to information, learning DisplayFab methods is a non-trivial challenge. The only significant work that we found on this subject was the Decochrom series of workshops, spearheaded by Löchtefeld *et al.* [103, 104] where both aspects of learning DisplayFab methods and observing learning through DisplayFab are carried out. Within PersonalFab, a number of works explore learning and pedagogy within the context of DisplayFab. Eisenberg explores the use of personal fabrication within education, with a focus on how each area could reciprocate in shaping the other [34]. In their workshop, Stickel *et al.* explored the role of 3D printing in education and innovation towards "common good and education" [180]. Overall, this line of research questions remain underdeveloped in PersonalFab as a whole but specifically within DisplayFab.

#### 5.3.2 Challenges and opportunities.

*Challenge 15: Non-specialist learning of DisplayFab.* The key challenges relating to how non-specialists learn, link to the dispersed nature of DisplayFab materials and technologies. Key questions arise relating to the complex structures produced and the differing non-specialists skill-sets and learning rates. Support for learning is another important related issue, with preliminary work within the Decochrom project providing workshop-based support, and other self-taught isolated examples [104]. However, structures for teaching and supporting the development and adoption of DisplayFab methods must be developed in conjunction with expansion of this research.

*Challenge 16: Learning through fabrication.* Building on Stickel *et al.*'s work [180], the opportunity to develop means for people to learn through fabrication is unique to DisplayFab because of the focus on interactive objects. If development of further DisplayFab technologies can occur in tandem with user involvement in processes then DisplayFab can provide the opportunity to expand otherwise insular areas of HCI research regarding interactive devices and organic user interfaces. The potential to teach about human computer interaction through DisplayFab represents a research opportunity with significant breadth spanning the field of HCI.

## 6 CATEGORY 3: FEEDBACK AND INTERACTIVITY

### 6.1 Interactive fabrication

*6.1.1 Context and related work.* The concept of interactive fabrication, developed by Willis *et al.* [209], involves merging computational fabrication with traditional craft-based fabrication techniques to explore the design process. The process of translating artistic painting or crafting methods over to display fabrication and scaling up electronic processing, can be conceptualised by the scale Willis outlines, of **sculpting to digital fabrication to interactive fabrication**. Many works (such as [44, 92, 164, 191]) look at finding solutions that sit between these categories to optimise the process for makers (Figures 13 and 14).

**Figure 13: Interactive Fabrication works developed within PersonalFab: MixFab [203], FormFab [125] and Adroid [190]. All images copyright maintained by original owners: ACM**

Work on novel interactive fabrication systems pushes the boundaries of synchronous design and fabrication such as by using mixed reality to support makers. Continuous interactive fabrication has notably been explored by Peng *et al.*'s custom "RoMA" [140] where continuous user design and input via AR is applied through a robotic arm-based 3D printing extruder. RoMa builds on Weichel *et al.*'s MixFab [203] that looks at a mixed-reality environment for designing and fabricating inactive objects. Mueller *et al.* [125] show responsive interactive fabrication beyond turn-taking set ups, through fabrication based on reformable thermoplastic sheeting. Meanwhile in FusePrint [225], zhu *et al.* explore integrating physical real-world objects in the fabrication process to facilitate design. Mitterberger *et al.* [113] use AR combined with an automated set up for spraying in order to deposit plaster in an interactive fabrication pipeline with an industrially scaled set-up. Meanwhile Fossdal *et al.* [43] explore control of a fabrication tool (for engraving) directly within a CAD environment, blending the line between machining and designing. Otherworks explore asynchronous autonomous and handheld processes [157, 187] as well as realtime error correction [152, 202] and integrated design [2]. Such interplay and intervention methods, while applied to personal fabrication of inactive objects, are clearly areas that DisplayFab has potential to be expanded into.

**Figure 14: Interactive Fabrication works developed within PersonalFab for 3D printing and plastering: RoMa [140] and "Interactive Robotic Plastering" [113]. All images copyright maintained by original owners: ACM**

#### 6.1.2 *Challenges and opportunities.*

*Challenge 17: What do interactive DisplayFab fabrication tools look like?* The challenges of interactive fabrication are compounded by a divergence and diversity in materials and methods. Recent work has portrayed spraying as an optimal measure. However, following the dynamic machining trends in 3D printing, research must develop in a flexible way to adopt new deposition methods. We also question what interactive fabrication looks like in the DisplayFab context. For example, is it turn-taking or continuous and how is support embedded? This challenge provides a research opportunity to start convergence and centralisation of processes as optimisation of methods and materials is carried out.

*Challenge 18: How do we build interactive fabrication tools?* Developing bespoke machines and systems in conjunction with users represents both a challenge and an opportunity. Further difficulty surrounds the unclear nature of potential user groups which in turns lends itself as an upcoming research opportunity. As a key example, Fossdal *et al.* [44] exploring making digital fabrication machines accessible through "The Fabrication Axis" - exploring multiple portable fabrication machines.

## 6.2 Testing

#### 6.2.1 *Context and related work.*

Formalised testing structures for devices and fabrication steps are yet to be developed, and we identify that they are fundamental to its expansion. Within DisplayFab devices often fail to act as predicted and although steps can be taken to fix interactive devices that are produced, it is not always clear as to what these steps are. This encourages development of testing platforms and quality control structures, as well as a unification of evaluative structures for researchers. Due to DisplayFab's embryonic nature it currently lacks unified testing platforms and there is limited related work supporting. We argue that this elevates the opportunity for research.

#### 6.2.2 *Challenges and opportunities.*

*Challenge 19: Developing unified testing across systems and materials.* Either development of singular testing systems that are able to support different materials or the process of unifying and bringing in line multiple supporting testing structures represents a major challenge for DisplayFab. As with Challenge 14, re-appropriation of material science evaluative measures are key to comparative development between research projects (e.g. in [218]. However, the early-stage nature of DisplayFab means that effective development of evaluative procedures at this stage could maximise future impact and the shape of the field. As an example, we suggest scope for work on measuring factors inherent to interface design such as the "fabricatability" of a process (ease of fabrication by different skilled makers). This is an underdeveloped area, although works such as [184] provide initial explorations into the usability of fabrication methods.

*Challenge 20: Ongoing maintenance of testing structures.* Even in the currently underdeveloped state of DisplayFab, the maintenance of a testing framework to support all appropriate materials and to update with the latest state-of-the-art research would be a monumental task. As DisplayFab develops, if it follows the patterns of PersonalFab, methods are likely to converge but deepen in terms of research and understanding. We suggest engagement with the maker community in this context (linked to the above topics of maintained material and methods information) through community support and integration in the future as an opportunity for research.

# 7 CATEGORY 4: RESPONSIBLE INNOVATION

## 7.1 Intellectual property

#### 7.1.1 *Context and related work.*

Ishii introduces the concept of "the pixel empire" [151], where corporate control over interactive devices limits the potential for expansion of human computer interaction. The continuation of this concept into "Radical Atoms" [66, 67] meshes with DisplayFab's potential to enable democratised fabrication through decentralised production beyond corporate influence. Unlike PersonalFab, DisplayFab lacks proprietary structures and adopted practices. Instead IP issues relate to the materials, use of them and the impact of being able to produce devices anywhere that can convey protected information. We draw on existing work to suggest directions for democratisation of technological practises and the use of maker spaces [102, 189].

#### 7.1.2 Challenges and opportunities.

*Challenge 21: Democratization and ownership of materials.* Building on Sweeney *et al.*'s concept of displays as a material [185], within the vision of DisplayFab, we view display materials and functional displays themselves as converging structures. In this light, Ishii's vision of freedom from the pixel empire cannot be achieved through prefabricated modules and we turn to liberated display materials, for a solution that still relies on a physical interface (beyond technologies such as augmented reality). This brings up specific challenges regarding proprietary structures and materials, such as E ink (as explored in FabricatINK [54]). We propose addressing these challenges both through conforming approaches such as collaborating with manufacturers as well as radical approaches including contradiction of legal issues and drawing inspiration from hacking, upcycling and repurposing work.

*Challenge 22: Responsibility for digital output.* A different challenge to consider at this early stage of DisplayFab is the manner in which information is controlled between digital displays without clear ownership when divides between device, material and pixels are blurred. Developing social, ethical and legal arguments for digital graffiti will be necessary alongside DisplayFab. At this stage, we see development of this legal discussion happening hand in hand with material and control set-ups but, as above, a dynamic research agenda is required to adapt to the on going issues. An analogy can be drawn between development of piracy and ownership of digital space.

### 7.2 Sustainability

#### 7.2.1 Context and related work.

PersonalFab issues regarding promotion of unsustainable materials such as plastics, resins and single use metals are directly relevant to DisplayFab, with greater significance due to the nature of the materials involved. On the other hand, we suggest that adaptations, such as more specialised use might lessen DisplayFab's impact. The materials used in DisplayFab are often damaging solvents such as toluene and acetone [207]. Materials such as metals and EL phosphor have inherent sustainability issues regarding procurement. We separate issues to be addressed into sustainable procurement of materials, byproducts damaging the environment, devices themselves impacting their environment and disposal of materials.

Work within PersonalFab shapes these challenges. For example, Wall *et al.* [198] replace inert parts of 3D prints (infill) with scrap material to create objects that have less net waste. Applying similar approaches to DisplayFab might take the form of appropriate substitutes for non-active materials such as EL dielectric layers. Wu *et al.* [210] explore the design with disassembly prioritised to facilitate reusibility of components with practises that should be built on in material-centric fabrication while Stemasov *et al.* [178] implement purposefully short-lived artefacts. Meanwhile, Meena *et al.* [111] explore self-powered interfaces and we suggest exploration of similar measures as a key necessity for DisplayFab moving forwards, only increasing in line with the scale of its adoption by makers.

#### 7.2.2 Challenges and opportunities.

*Challenge 23: Sustainable procurement of material.* Sustainable materials are a key consideration around the development of fabrication and more specifically DisplayFab due to the toxicity and energy expenditure in current material production. With regards to active materials, some display types use rarer energy intensive materials in their personal fabrication. For example EL uses encapsulated phosphor [107]. Display materials exist currently within prefabricated displays that use less harmful materials. A key example of this is E ink [54, 70]. When it comes to conductive traces, sustainable electronics fabrication is being explored, such as through recent work by Koelle *et al.* [93] exploring bioplastics in conductive materials. DisplayFab requires such development.

*Challenge 24: Harmful materials as by-products.* A different category of environmental impact comes from overspill of materials through fabrication processes. Recent works, such as "Sprayable User Interfaces" offer the potential of iterative, additive spraying to produce display types, reinforced in hobbyist use [96] and commercial implementation [106]. The atomisation of potentially dangerous and environmentally unfriendly chemicals (e.g. toluene), as well as issues relating to over overspray, must be considered when promoting these methods and research opportunities. Mitigating impact while still harnessing the potential of these materials is a clear challenge.

*Challenge 25: Environmental impact of devices.* Use of devices can have a negative environmental effect that must be addressed, through energy use and control. As an example, EL displays draw a significant amount of power compared to LEDs [95]. Scaling up adoption and use of DisplayFab can only be done with responsible reflection on this impact and minimising its effect through the adoption of efficient materials such as those with bistability and low power consumption. Additionally, light emitting display types, such as EL could contribute towards light pollution.

*Challenge 26: Device disposal.* In tandem with responsible development of materials, we must work on appropriate disposal of systems, as investigated by Song *et al.* [175]. We suggest incorporating these factors in the design of DisplayFab devices. Responsible development and propagation of fabrication methods must be researched with this in mind, building on patterns seen within 3D printing. Song *et al.* extend these themes, exploring beneficial, aesthetic and otherwise desirable of fabricated objects specifically that have and are undergoing damage [176]. We note that the multimaterial structures of EL and EC structures within DisplayFab make recycling a challenge, and work within Sprayable User Interfaces [207] addresses initial steps in this direction through removal of conductive base layers.

### 7.3 Health and safety

#### 7.3.1 Context and related work.

Recommendations are thoroughly given in the majority of DisplayFab works for personal precautions and risk management, however a direct assessment or comparison between the risks of various processes is lacking. We identify three important risk areas: 1) key dangers relating directly to active materials, including solvent use, unknown content and impact and makers producing their own materials. 2) Risks relating to fabrication process (such as hand held atomisation of materials through spray deposition [132, 207]). 3) The control for different active materials such as high voltage use [134] and potentially damaging tools such as projectors or lasers for photochromic activation.

#### 7.3.2 Challenges and opportunities.

*Challenge 27: Domestic fabrication limitations.* The most important challenge regarding health and safety revolves around the *target domesticity* of DisplayFab. Is DisplayFab intended for home use by non-specialists or maker labs. 3D printing, specifically resin printing has shown both how for semi-specialists, handling of dangerous chemicals is manageable within domestic settings but also, with increasing uptake, that centralised safer non-domestic hubs such as hackspaces or makerlabs are taking on the fabrication tasks. When applied to DisplayFab, investigation into location of fabrication processes and who will carry them out is therefore needed. Carrying out material and deposition research in tandem provides the opportunity to allow end use to shape research directions.

*Challenge 28: Material and process safety development.* There is a great research challenge in the development of safe active materials and processes for deposition, focusing on current projected use of domestic personal fabrication. E ink and EC should be exemplars in this with work needed to produce safe-to-handle active EL material components. Further extensions to this research includes application areas of DisplayFab covering on-skin applications such as digital tattoos and make-up where health and safety has an even greater significance.

### 7.4 Ethical impact on users

*7.4.1 Context and related work.* A direct result of promoting and facilitating the propagation of fabricated interactive devices is the potential for such displays everywhere. As part of DisplayFab's goal to provide a roadmap of research that can facilitate adoption and implementation of interactive device fabrication, we outline initial challenges following the early stages of adoption. We propose considering the impact that wide-scale interactive device deployment will have beyond the makers of the devices and rather to the **users** of these devices. This subsection encompasses the potential impact of end devices on people. There is very little work addressing this in the context of DisplayFab, in itself a future challenge that should be addressed. However within HCI there is a breadth of related research. Specifically, Brudy *et al.* [19] provide a scale to classify different user categories, that we can apply to fabricated displays, on a spectrum ranging from *near->personal->social->public.* We propose further investigations into DisplayFab applications with a focus on encouraging makers to frame potential impacts on these different ranges of user group.

We categorise key considerations into several groupings. Ownership of information when the medium has unclear ownership is already touched on above under IP, however in the context of ethical impact, we raise the discussion point that information used in this way has a greater impact of being used maliciously or with intended *negative impact* (for example adverts everywhere that users are unable to avoid and can be positioned without ownership of the substrate location). From the maker's and user's perspective, there is little discussed from the perspective of *security* for DisplayFab. Within PersonalFab, Adkins *et al.* [1] discuss security challenges relating to dispersed methods over multiple different companies. ElSayed *et al.* [35] explore security issues within precision replicability, while Tiwari *et al.* [192] discuss the dilution of clarity relating to additive manufacturing.

#### 7.4.2 Challenges and opportunities.

*Challenge 29: User vs maker.* The difference between the user and the maker of the display raises a set of potential research challenges around how to liaise in an appropriate way between user groups that may never interact except for through individualised products. Developing a frame within which this should be approached requires further research. Ahmadi *et al.* explore improving awareness of diversity issues within maker spaces through themes of openness covering raising awareness, matters of space, shared language and co-production of different makers [3].

*Challenge 30: Malicious use and passive display impact.* The ability to convey information anywhere involves often negative impacts such as vandalising graffiti (differentiated from graffiti art) and detrimental advertising. This is specifically important given the recent innovations within DisplayFab deposition methods incorporating location agnostic methods such as spraying [207]. Scaling methods of depositing materials to include active materials, as advocated within DisplayFab has the potential to scale these problems through this digital medium and this must be mitigated at the earliest stage possible through further exploration, research and responsible development.

## 8 DISCUSSION

Beyond discussion within specific challenges, we provide a meta-discussion on the projected goals of DisplayFab, the subfield's timescales, and the use and derivation limitations of the framework. We also outline an overview of the challenges presented in this paper.

### 8.1 DisplayFab's interdependence with HCI

Through the promise of automated deposition and adherence to material tenets of additive manufacturing, DisplayFab provides two pillars of contribution to support physical computing's goal of decentralised readily-available free-form interactive devices:

- **Fabrication by non-specialists:** DisplayFab's use of active materials to separate layers of light-emitting of colour changing components alongside integrated touch sensors, opens potential for automation in fabricating interactive objects, and following the footsteps of 3D printing, uses by non-specialists.
- **Truly free-form devices:** Deposition of active materials and the technologies developed within DisplayFab research allow for fully configurable device forms, beyond assembly of pre-fabricated component forms. DisplayFab offers unique form-factors and display structures that would otherwise not be achievable, as a direct result of building structures from malleable materials.

DisplayFab represents the intersection between key interest areas within HCI: 1) research into fabrication practises such as interactive fabrication [209], combined with 2) the longstanding vision of free-form interfaces that can be realised via the rapid production of interactive objects [10]. We contextualise DisplayFab's end goals beyond just usable methods to prototype free-form devices for research. Beyond even *organic user interfaces* [62], *tangible user interfaces* [68] and *radical atoms* [66], DisplayFab points towards new means to unlock other research visions such as pervasive [160] and

| | | |
|---|---|---|
| 1) Hardware and Material | Active Materials | Challenge 1: Procurement of materials<br>Challenge 2: Diversification of materials<br>Challenge 3: Device Performance |
| | Fabrication Hardware | Challenge 4: How to improve resolution and fidelity<br>Challenge 5: Topologically free-form shapes<br>Challenge 6: Scaling up of fabrication production |
| | Location and Availability | Challenge 7: Access to processes for a non-specialists<br>Challenge 8: Portability of systems<br>Challenge 9: Control, stimulus and electrode attachment |
| 2) Conception and Software | Design support | Challenge 10: What does DisplayFab design support look like?<br>Challenge 11: How do we build bespoke design tools?<br>Challenge 12: Prototyping of DisplayFab structures |
| | Domain knowledge | Challenge 13: Unification of domain knowledge<br>Challenge 14: Further material exploration |
| | Learning | Challenge 15: Non-specialist learning of DisplayFab<br>Challenge 16: Learning through fabrication |
| 3) Feedback and Interactivity | Interactive fabrication | Challenge 17: What do interactive DisplayFab fabrication tools look like?<br>Challenge 18: How do we build interactive fabrication tools? |
| | Testing | Challenge 19: Developing unified testing across systems and materials<br>Challenge 20: Ongoing maintenance of testing structures |
| 4) Responsible Innovation | Intellectual Property | Challenge 21: Democratization and ownership of materials<br>Challenge 22: Responsibility for digital output |
| | Sustainability | Challenge 23: Sustainable procurement of material<br>Challenge 24: Harmful materials as by-products<br>Challenge 25: Environmental impact of devices<br>Challenge 26: Device disposal |
| | Health and Safety | Challenge 27: Domestic fabrication limitations<br>Challenge 28: Material and process safety development |
| | Ethical Impact on Users | Challenge 29: User vs maker<br>Challenge 30: Malicious use and passive impact |

**Figure 15: A summary of the 30 challenges and opportunities derived from the DisplayFab roadmap.**

ubiquitous [108] computing through distributed interfaces [100]. Through DisplayFab, a vision of interactive artefacts customised to their use is painted. These implications differentiate DisplayFab from being merely a set of complex and unique prototyping methods and instead provide an end goal where prototyping can become production.

In exploring the validation of DisplayFab research, we face a critical question within HCI: how should we approach the scale of innovations in DisplayFab? Currently, within academic contributions we prioritize short-term usability with a limit on the consideration of long-term factors such as integration with existing workflows, generalised fabricatability and accessibility, which in turn limit the field's growth. We believe DisplayFab research should adopt a broader, long-term perspective in line with the promise that this research area has beyond enabling interaction research. This limits the ability for DisplayFab to provide research contributions as stepping stones towards larger contributions and fundamentally restricts the expansion of the DisplayFab field in a different respect. Transparency in reporting usability, including both successes and failures, is disparate and many presented processes are highly skill dependent, making it difficult to replicate methods accurately. Specifically, we advocate for categorizing and analyzing DisplayFab work within a long-term vision, prioritizing end goals over immediate usability concerns.

DisplayFab research is often targeted to an HCI audience, but we question DisplayFab's future and its relationship with HCI. We extend this discussion to consider whether DisplayFab has a place in research beyond HCI, such as the commercial sector, hobbyist communities, or other academic branches. In HCI, our contributions align closely with challenges in "interactive fabrication" and innovations in "design support" for interaction. Material science and engineering could better support "materials and deposition" methods, but HCI's user-centric approach remains influential. Societal challenges, as seen in PersonalFab, are often addressed outside academia through commercial ventures, legal actions, and projects like RepRap [149] and the Maker movement [109]. Extending the concept of democratisation [189], this has the inherent benefit of development occurring in a space relatively independent of corporate agenda (e.g. FabricatINK [54]), which aligns with the potential of DisplayFab to empower makers. Instead of waiting for DisplayFab's challenges to follow a similar path, we propose proactive engagement by researchers. We propose closer collaboration with the Maker movement and industry to harness their contributions to additive manufacturing. Emulating established industrial relations from other engineering disciplines can help explore DisplayFab's potential and overcome limitations. Ultimately, DisplayFab finds its primary home within the HCI domain, due to "designing for interaction". However, as it continues to evolve, DisplayFab holds the potential to diverge and establish itself as an independent field.

### 8.2 Displayfab's timescales

*Evolution of DisplayFab relative to 3D printing:* The nature of DisplayFab's derivation is that we directly compare it to the personal fabrication of inactive objects. The three factors differentiating its challenges and specific research needs (its early-stage nature, with the others being complexity and designing for interaction), are likely to dissipate over time as the field is further developed. We posit that despite its divergences, DisplayFab may mirror the patterns of growth, development and adoption as PersonalFab and more specifically trends in 3D printing, requiring convergence of methods and significant development before commercialisation and widespread adoption.

Although it is likely that DisplayFab can leverage innovation and the shape of research development from PersonalFab there is also a significant possibility that a number of the research challenges presented are immutable with our current technological limitations and through this, applying the shape of the PersonalFab and 3D printing revolution to DisplayFab will be inaccurate. This takes the form of a consideration on how research is carried out in this area, but also a constraint on further research.

### 8.3 DisplayFab limitations

Our work has been determined by related work and our hands-on experience, however we acknowledge it's subjective perspective. We outline its limitations.

*Convergence of PersonalFab and DisplayFab:* Despite DisplayFab being motivated by core breakages in the PersonalFab framework, as its early stage of development diminshes through further research, we suggest that it is likely that the challenges within each of the two frameworks will converge. However, the need for DisplayFab as a variation on the PersonalFab framework will remain strong in the context of DisplayFab's increased complexity and the need to design for interaction. Indeed, one of the aims of this work is to provide a roadmap to support the development of DisplayFab into a situation similar to that of PersonalFab with widespread adoption. It is our vision that the PersonalFab framework will regain increased applicability to DisplayFab, and that through further development in this area the convergence between both frameworks and areas will provide greater opportunities for research. This could not only provide cross-pollination and economies of scale, but we also envisage an endgame where universal machines could produce both interactive and inactive 3D printed artefacts.

*Challenges beyond the scope of this paper:* There are areas that are deliberately not included in this work as a result of its derivation from the PersonalFab framework and what challenges that can be addressed as research contributions. The framework provides bounds on research challenges, however it also excludes certain research directions from its list of challenges and opportunities. As an example we highlight that we do not discuss how research is evaluated (which other similar frameworks do [131]). In this context, we do address this within discussion below under how DisplayFab and HCI intersect. However, we made the decision not to include it within the framework as a result of it being an adaptable "meta" question that we see as addressed through the means of experimental research themselves. As future work, we propose that scoping limitations within the definition of DisplayFab be expanded. For example the inclusion of non-visual kinetic [33] or haptic displays [8], or similarly non-additive manufacturing methods.

*Omissions from the roadmap:* Beyond evaluative measures, there is a possibility we have omitted key research directions beyond our own perspectives. We aspire for our work to be an adaptable structure that researchers and practitioners can update it as new challenges arise. This is also applicable to challenges becoming addressed or obsolete. We conclude that the DisplayFab framework is as comprehensive as we could make it, but also that it should be used as an adaptable structure relating to the challenges and opportunities for this research. In addition, we identify the subjectivity involved in identifying challenges for the DisplayFab framework. Specifically, challenges that we faced as makers ourselves and other reported are not inherently uniform relying on maker's lived experiences, perspectives and motivations. We look forward to seeing how DisplayFab will be used and further iterations on the framework structure.

## 9 CONCLUSION

We contribute the derivation of the *DisplayFab roadmap* to support development of the personal fabrication of free-form interactive devices. Dispray outlines a path for further research, developed through a targetted review of related work. This framework is structured as a reformation of the state-of-the-art PersonalFab framework and it contributes an outline of challenges and opportunities for the future of research within DisplayFab by identifying 30 key areas that need to be tackled. We aspire that this roadmap will inspire a re-convergence of DisplayFab methods, researchers and development to enable the vision of free-form interaction on-demand to support any use by makers of all backgrounds.

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