Digital -is- Physical: How Functional Fabrication Disrupts Ubicomp Design Principles

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ABSTRACT

Ubiquitous computing has long explored design through the conceptual separation of digital and physical materials. We describe how the emergence of the fabrication community in HCI will challenge these conceptual principles. The idea of digital material in ubicomp 'hides' lower level abstractions such as physical architectures and materials from designers. As new fabrication techniques make these abstractions accessible to makers, physical materials are being used to encode digital functionality. Form (traditionally physical) and function (traditionally digital) can be mutually expressed within material design. We outline how emerging printed electronics techniques will enable functional fabrication, current limitations and opportunities for end-user fabrication of functional devices, and implications for new principles that emphasise combined physical design of form and function.

CCS CONCEPTS

• **Human-centered computing → HCI theory, concepts and models**.

KEYWORDS

Functional Fabrication, Thin Film Device Engineering, Tangible Design, Mixed Reality, Ubiquitous Computing

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1 INTRODUCTION

In Onion's study of Steampunk culture [15], she quotes the Catastrophone Orchestra and Arts Collective's cultural desire for machines that retain some accessibility, "*Steampunk machines are real, breathing, coughing, struggling and rumbling parts of the world. They are not the airy intellectual fairies of algorithmic mathematics but the hulking manifestations of muscle and mind, the progeny of sweat, blood, tears, and delusions. The technology of steampunk is natural; it moves, lives, ages, and even dies*". Such work draws inspiration from the first industrial revolution, despite the purpose of steampunk machines being principally cultural rather than functional. In communities of machine enthusiasts, whether steampunks, vintage car owners, traction engine mechanics, and builders of replica early computers, relay computers and Difference Engines, there is an emotive, almost comforting aspect to understanding, building and using machines.

The discomfort of disengagement from computers through the layers of miniaturisation and abstraction which have become so widespread provides exactly the right cultural inspiration for fabrication in HCI: the attempt to enable manufacturing of physical, functional objects and devices by end users [1].

In this paper, we describe the implications of the emerging fabrication community in HCI for the mixed reality design principles which have underpinned ubiquitous computing. The past two decades have seen an explosion in paradigms which combine physical and digital interfaces in a range of conceptual forms to ubiquitous computing. Tangible [9], embodied [4] and ubiquitous [21] computing have promoted the design of hybrid interfaces in various ways, but all these approaches share in common the notion that digital and physical resources have different and complementary properties and that, in contrast to earlier Graphical User Interfaces (GUIs), physical interface design deserves at least equal status to digital interface design. Our response is informed by Benford and colleagues'[11] work on mixed reality orchestration, in which performers weave form and function into an illusion of trajectories between physical and digital worlds.

As functional materials gain prominence, form (traditionally physical) and function (traditionally digital) become increasingly difficult to separate according to this physical-digital divide. This paper outlines the materials and techniques that are driving this progress, and the design themes of agency, creativity, economy and sustainability that will be disrupted by the changes.

2 FABRICATION EMPHASISES PHYSICALITY

Recently we have seen an increasing interest in material design in computing [22] and the emergence of maker communities with craft knowledge across tangible computing, product and industrial design, unconventional electronics, robotics and visual and performance arts [8]. Recent work in HCI on tools to support fabrication includes laser cutting [13] and growth in the applications of cheap 3d printing [12]. There has also been an increase in the broader use of conductive materials to design and print interactive device prototypes [14]. This return to crafting and making is an important agenda for restructuring the boundaries in society between producers and consumers. The emergence of Personal Fabrication

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[1] in this context is potentially revolutionary, as end-users are enabled to become end-producers, making things that they need on demand at home or in the workplace, recycling locally to enable an improved circular economy, and acquiring greater awareness of the sustainability of their own consumption as a result.

Baudisch and Mueller [1] describe personal fabrication as conceptually underpinned by two complementary operations, an Analogue-Digital (AD) converter, such as a 3d scanner, and a Digital-Analogue (DA) converter, such as a 3d printer. Intermediate digital data can be seamlessly edited in digital form and then turned back into a copy or new physical object. By this account, fabrication is strongly reliant on previous conceptual models of ubiquitous computing and mixed reality, as a synthesis of physical and digital tools and techniques.

However, in this paper we want to present a more conceptually disruptive view of fabrication, one which specifically takes into account the personal fabrication of electronics, or 'functional' fabrication. The many fabrication materials explored in [1] include conductors and semiconductors, electrically responsive materials which enable printed electronics. We suggest that functional fabrication is not just a potential application of the wider fabrication landscape, but could radically change the way designers conceptualise 'digital' systems.

Digital systems are themselves built upon physical architectures, albeit these are often hidden by layers of abstraction. Notions of digital material are founded on well-established computing and communication abstractions which mask the behaviour of an ultimately physical system. As we have become accustomed to authoring software, we have forgotten that the same algorithms can be embodied in physical materials. Functional fabrication enables the idea that digital material is an illusion built upon physical foundations that are newly accessible to the user-as-maker. Indeed, human inputs such as touch sensing, outputs such as LEDs, transistors for building architectural components such as memory or simple processors, even solar cells for supplying power can all be rapidly printed. The materials and processes to do so are making their way out of labs and factories and into fabrication platforms which are becoming increasingly accessible to end users.

3 FABRICATING ELECTRONICS

The wider fabrication ecosystem has been underpinned by cheap microcontrollers such as Arduino consisting of circuit boards mounted with silicon chips alongside accessible software interfaces for designers. While such platforms have been hugely valuable for rapidly producing prototypes, significant economic barriers remain when scaling up production, and physical inefficiencies in these 'circuit board plus silicon' approaches constrain size, form and aesthetics. Often, product designers must address form and function separately, form through traditional hands-on materials engagement, and function through constrained choices of existing physical hardware and software APIs.

A step change in the capabilities and scale of personal fabrication could be enabled by designing, deploying and evaluating new design tools that make accessible material science innovations and electronic design and manufacturing techniques. Three particular innovations are important in the context of enabling end-user access to electronic fabrication: functional materials, thin film devices which use these materials, and accessible printing tools and techniques to create these devices.

3.1 Organic Electronics

Functional plastics are cheap conducting and semi-conducting organic polymer materials that can be arranged or printed to build circuits, transistors, sensors, displays and many other electronic components [2]. This class of materials is particularly interesting because it provides opportunities to cheaply build electronic capabilities that are tightly coupled or even merged with product design materials. The potential level of physical and functional integration achieved by using electronic materials is orders of magnitude greater than Arduino-like approaches.

Since the discovery in the 1970s that some organic polymers could act as electrical conductors, there has been steadily growing interest in materials science research in conducting and semiconducting plastics, so-called 'plastic electronics'. These materials can come in a number of forms, but are often processed as liquids or suspensions that can be sprayed or spun onto surfaces [3, 19]. Functional plastics can have conductivities approaching those of metals, yet are inexpensive to produce in quantity [6]. Semiconductors are a special case in which the polymer is 'doped' to generate materials called p-type (shortfall of electrons) or n-type (surplus electrons), useful in thin film devices (see below). Major commercial innovations include Organic Light-Emitting Diodes (OLEDs), and Organic Field Effect Transistors (OFETs).

There is a strong science and engineering research base in polymer electronics, focusing on measuring and improving the performance and scale of devices in order to approach the performance of silicon. Typically silicon-based components can already be emulated in plastics, for example existing work shows that functional plastics are capable of enabling touch sensing, displays, small computers for processing information, memory, and printed antennas [6].

The performance of plastic electronics approaches is not yet comparable with silicon approaches, so for example the OFET has not yet replaced the MOSFET in commercial chip design. However, we are increasingly seeing other benefits to plastic electronics. The clearest benefit is that the materials can be processed at low temperatures, enabling flexible substrates to be used in the printing process without damaging them with heat. This creates opportunities for flexible displays and devices which would not be possible with high temperature, brittle silicon processes. The ability to process at low temperatures also opens up opportunities for integrating plastic electronics in end-user fabrication, because the processes can potentially be more easily encapsulated into safe and accessible consumer platforms.

3.2 Thin Film Device Engineering

One driver of increased interest in these materials over the past two decades has been the massive growth in their use for thin film device engineering. Thin film devices are essentially 'sandwiched' layers of such functional materials which interact electrically with one another. Many different devices are possible depending on the ordering and materials used in each of the sandwich layers.

Typically, the surrounding 'bread' of the sandwich are electrodes, conductive layers that transport current to and from the device. The 'contents' of the sandwich are then layers of dielectric, semiconducting, light-emitting or light-activated materials, depending on the device being created.

A common feature of thin film devices is a thin layer of dielectric (electrically inert) material. Electrical potential on the electrodes can exert influence across the dielectric layer such that the excess holes or electrons in the semiconducting material start to conduct. This creates a 'sluice gate' electrical effect which works like a switch. The field effect could activate light emission in the case of Organic Light Emitting Diodes (OLEDs), transistor switching in the case of Thin Film Transistors (TFTs), or be activated by light in the case of Thin Film Photovolatic solar cells (TFPV) [10, 20].

As an electrical field effect is required across the dielectric layer in these devices, precision is required to make this layer very thin and uniform for predictable low voltage performance, but with no actual holes through it which would cause a short circuit. So, there are physical limits and optimisations to thin film engineering which have for some time made it difficult to move out of the laboratory or factory. Nonetheless, as these techniques become better understood, researchers have begun to explore how accessible printing techniques could be applied to thin film engineering. Such devices are small enough that they can be used as thin coatings to product designs, or even layered in tiny structures to create complex larger artefacts.

3.3 Printed Electronics

Physical demands on thin film layering precision have traditionally required 'clean room' approaches to avoid impurities which could breech layers, as well as expensive and complex coating techniques such as Plasma Vapor Deposition (PVD) to create thin enough films to be electrically appropriate. Our third set of innovations centres on emerging printing techniques which could bring thin film devices out of the lab and into maker spaces. This could allow designers to manipulate materials of form and function together, designing efficient and scalable electronically-functional prototypes based on familiar personal fabrication tools.

So far HCI research on fabrication processes with functional materials has been limited principally to technical processes. An increasing body of publications that explore approaches such as screen printing [14], hyroprinting [7]. electrospinning [16], inkjet droplet-on-demand [19], roll-to-roll printing [17] and spray coating [3] all have early adopters within the HCI fabrication community. These early technical explorations are the 'thin' end of the wedge in which printed electronics will be increasingly incorporated within accessible makerspace prototyping processes, and increasing efficiency and scale of functional materials processing makes it way from manufacturing into personal fabrication. However, beyond making the technical processes more accessible, there are social and technical abstractions which will need to be addressed to integrate functional fabrication into existing ubicomp designs.

4 PHYSICAL, AS IN 'OBEYS THE LAWS OF PHYSICS'

The notion of a user interface which resides 'above' such physical systems contributes to the conceptual separation between digital and physical, visible and invisible, tangible and intangible, embodied and disembodied. The term physical literally implies that the system obeys the laws of physics, and therefore includes the behaviour of 'unseen' physical systems. For example, computer behaviour may be physical but perceptually invisible due to carrier frequency such as wireless transmission via radio signals; or due to miniaturisation such as the nano-scale transistors that make up modern memory and processors which have invisible electrical switching behaviours characteristic of semiconductor-based computer architectures. We have become accustomed to the idea of digital design, but invisibility often leads us to forget how information itself is physically transmitted, transformed, encoded and represented, and that this may obscure new design opportunities.

When we imagine 'the digital', we often resort to a disembodied model of 'data' or 'information'. Suchman [18] draws on Katherine Hayles' How Information Lost its Body to explore the need to reverse the immateriality of information, suggesting it should be inseparable from its material and social instantiation in the everyday world. A key point of Suchman's thesis is that the engineering challenges and labour involved in making technologies are masked by current design approaches which use highly abstracted notions of intelligence and autonomy to hide the work on the ground required to make technologies work. This challenge requires that we return to the foundations of computing to understand how the physical body of digital information has been obscured in our current models of computing design. Clearly the computers themselves are still there; so why does their manifestation remain so abstracted from our consciousness, and how do these physical systems remain so well hidden in plain sight?

5 FABRICATION DISRUPTS ABSTRACTION

Although abstractions exist for good historical reasons, they can create inertia in computer designs which would otherwise be open to the diverse ideas increasingly recognised in fabrication, for example cultural or artistic values; or efficiency in material consumption rather than computational efficiency.

Computing history is characterised by abstraction of designs to increase efficiency, share standards and manage complexity. Abstractions help reduce the need to monitor or understand how computers work, inserting layers of complexity encased within veneers of simplicity to make computers more widely accessible. The computer science literature of the mid-20th century provides ample evidence that computational architectures themselves were already becoming 'unassailable'. In 1962, Doug Engelbart wrote:

> Sophisticated capability results from clever organizational hierarchy so that pursuit of the source of intelligence within this system would take one down through layers of functional and physical organization that become successively more primitive. A programmer could take us down through perhaps three levels. Then a machine designer could show us how the different hardware (e.g., random-access storage, arithmetic

> registers, adder, arithmetic control) are organized. The logic designer could then give us a tour of how pulse gates, flip-flops and AND, OR, and NOT circuits can be organized, a circuit engineer could show us how transistors, resistors, capacitors, and diodes can be organized. Device engineers and physicists could take us down through more layers. Soon we have crossed the boundary between what is man-organized and what is nature-organized, and are discussing the way in which a given physical phenomenon is derived from the intrinsic organization of sub-atomic particles, with our ability to explain succeeding layers blocked by the exhaustion of our present human comprehension. (abridged from [5])

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In the 1960s, machine architectures were already considered complex and the labour required to design them was starting to be distributed across different roles from physicists through to software engineers. Nonetheless, Engelbart remained the product of a generation which closely understood the nature of these machine architectures. Although machines of the 1960s were established in a hierarchy very similar to today's computers, they were not of the same scale of miniaturisation nor the same level of abstraction as current computers, for example even in the 1970s machines such as DEC's PDP-11 still closely tied programming operations to machine architecture, using assembly languages and physical switches which directly corresponded to and represented processor and memory instructions. Nonetheless, even these direct architectural interfaces were displaced proxies for the physical processes which took place on silicon designs.

The subsequent success of the next generation of high level programming languages, operating systems and the GUIs they coded meant that almost two decades would pass before researchers began again to ask serious questions about the physical design of computing interfaces. Work emerged from a demand to re-introduce physical design to the digital interface, and that has happened in a variety of ways, whether physicality came in the form of the 'real world' contrasted with virtual reality as in mixed reality, physical objects contrasted with graphical objects as in tangible computing, or social forms of physicality contrasted with cognitive forms of digital information as in embodied computing [4]. Ishii and Ullmer's vision of Tangible Bits [9] is an important example, which contrasted digital-only interfaces with physical-digital interfaces that combine the best of both 'materials', re-emphasising the design of hands-on devices and their interoperation with information. Tangible interfaces reach across the interface to identify correspondences between 'bits' and 'atoms'. The tangible computing paradigm has formed the basis of a programme which re-respects physical interface material and people's engagement with it.

However, the fabrication perspective suggests that the bits are also being stored, manipulated and calculated using atoms, in addition to any other interface design correspondences between these supposedly different mediums. Counterintuitively, tangible interfaces also reinforce the notion of a digital interface by giving it equal status to the physical interface, only diverging from digital-only (graphical user) interfaces. Ishii et al have expanded their vision to include Radical Atoms [8] – actuated and miniaturised interfaces which exhibit physical actuation and material dynamics. Nonetheless, this vision still accepts primacy of digital material as a concept by using actuation to present digital behaviours in highly material ways. Embracing functional fabrication requires that we fully reconsider digital design.

6 FABRICATION CHALLENGES DESIGN

Despite early examples, significant work in personal fabrication is still needed to move the audience for functional fabrication from materials scientists and engineers towards software engineers, product and interaction designers. The lack of 'high level' design innovation is not a weakness in the materials science itself, but rather in the kind of work that would naturally fall within the HCI remit âĂŞ forming freely available platforms and standards, comparable to Arduino-like approaches, which are agnostic to the shifting scientific landscape.

One specific challenge is to understand how to balance and combine the materials that give a product form and the materials that give it function. Should form follow function, or function follow form? Could we compose functional building blocks such as thin film devices into layers which then build up into desired tactile, structural and mechanical properties? Is it better to use algorithms which automate the layout and placement of functional materials within a designed form, similar in approach to the automatic routing of circuit boards? Whichever design approaches emerge, there are reasons for believing that local functional fabrication could enhance current design processes. Ubicomp abstractions although highly efficient and complex, can create undesirable personal and societal effects, and some positive effects could be encouraged by considering local design, not least the re-emergence of traditional craft in bespoke product design processes. Some motivations are to enhance holistic design opportunities, some to allow better reuse of materials or designs, and some to enhance human values like agency and creativity.

We would expect to see potential advantages in helping users understand, manage and creatively manipulate how systems work. Abstraction of technical complexity often reduces expertise in the behaviour of the abstracted layers. Even among expert computer scientists it is rare that a single person understands in detail the design of an entire modern computer at all layers. This challenge leads to many 'high level' design problems such as Wirth's Law [23], which suggests that increases in hardware speed driven by Moore's Law are effectively compensated by parallel decreases in software and operating system efficiency, because these layers are coded with minimal understanding of physical architectures and compilation processes.

There may be economic effects of local functional fabrication, for example undermining the separation of silicon design and manufacture in computing. Intel made a single investment of 9 billion dollars in its 22 nanometre fabrication process in 2011, a process already made redundant by 14 nanometre and subsequent architecture roadmaps. The fact that there are limited sources of transistor manufacture and very high barriers to entry means that most chip design companies are 'fabless', leading to slow design cycles, long lead times, and disengagement of the electrical and electronic design community from its target materials and manufacturing processes.

A key outcome will be environmental impacts: typically we cannot reuse old electronic components in new designs because the integration of materials at the silicon or even circuit board component level are so bespoke to the individual product that we have little sense of how to extract and reuse them. Clearly modular reuse of electronic components would be an order of magnitude more energy efficient than attempts to recycle them as base materials. However, reduction of waste and shortening supply chains is not a panacea. Functional fabrication will also require engagement with the circular economy and material recycling communities, as well as understanding how to design for reuse when the hands-on shaping of a range of physical materials is also the shaping of functional digital behaviours. Where physical and digital design converge in material design, new opportunities are presented, but new threats are also envisaged.

7 CONCLUSIONS

This paper has described the emergence of functional fabrication, and the idea that this enables physical materials and computer architectures to be accessible as interfaces. This approach is to some degree a development of hybrid physical/digital design programmes such as tangible computing and mixed reality in the way that they understand digital material sceptically as an abstracted allegory rather than as 'real' design material. However, it will go further to place the design of form and function together back into the product designers' hands. For HCI, functional fabrication makes us question the value of mixed reality approaches in ubicomp design. This paper has argued that the reification of the digital in ubicomp frameworks has given legitimacy to disempowering and obfuscating social and cultural effects of digital abstractions. Therefore, fabrication in HCI presents an opportunity more than just making things', but rather to re-make our conceptual relationship with technology in society.

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