Computational Infrastructure Materials for the Networked & Interactive Built Environment

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Abstract

From roads to roofs, homes to high-rises, my inspiration is the promise of building cyber-physical infrastructure for human interaction and enabling smart city applications. Unfortunately, there are several challenges in achieving this vision, due to the end of Moore's law, Dennard scaling, and our limited views on how computing systems are manufactured. To date, device manufacturing has focused primarily on miniaturization—packing the most functionality in the smallest form factor, despite our physical infrastructure being much larger in scale. We need to think creatively, design devices in new form factors (made in structural forms like walls, tables, facades, etc.) and materials of various kinds (e.g., those with extreme mechanical strength) that make up our built environments. There remain several challenges at the nexus of device power, form factor, and scale for designing our cyber-physical infrastructure.

In this dissertation work, I introduce "computational infrastructure materials" that enable us to build energy-efficient sensing, actuation, and communication in networked physical infrastructure (e.g., buildings, sidewalks) forms. Specifically, I look at how to enable our infrastructure materials (e.g., concrete, wood, composites) to do computation: (1) as they bear large force ($\sim$4000 lbs) (2) enable battery-free sensing and activity recognition at long distances ($\sim$70km), (3) actuate large-structures in response to user interaction, and (4) enable battery-free wireless communication. Additionally, I offer insights from the field about developing and deploying multi-modal tactile guidance surfaces. They contribute to an understanding of how computational infrastructure materials can support application areas such as accessibility.

Taken together, the capabilities introduced this thesis enable a range of applications in the built environment, such as digital buildings, accessibility, and ultimately towards creating sustainable and resilient cyber-physical infrastructure for human interaction. Finally, I summarize the contribution of this thesis and propose several future research efforts.

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Content Attribution

I would like to acknowledge that the icons used in Fig. 1.3 and Fig. 9.1 that are used in Chapter 1 and Chapter 9 are "Designed by macrovector / Freepik"

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Chapter 1

Introduction

1.1 Overview

The built environment, or the built world, refers to the human-made environment that provides the setting for human activity, including homes, buildings, zoning, streets, sidewalks, open spaces, transportation options, and more. We spend nearly 87% of our daily lives in buildings and built environments every day. Today, there are many demonstrated benefits to making our built environments ”smart” in areas of assisted living, personal health, sustainability, energy efficiency, accessibility, & overall quality of life.

Quite undeniably, sensors and the Internet of Things (IoT) are the workhorses of next-generation ”smart” built environments. The current approach has enabled low-cost sensors to be widely deployed, sense, and relay information about infrastructure from far away. Homeowners are increasingly inclined to upgrade their homes to an intelligent environment by investing in smart home technologies. As a significant push towards such advances, it is predicted that consumer Internet of Things (IoT) devices will reach several billion by 2025 [16]. It is also predicted that the economic value of the Internet of Things technology will reach $11 trillion USD by 2025 [79] and 30 billion IoT devices will be deployed by 2025. Similarly, in 2020 alone, a record number – nearly 150 million – of smart speakers such as Apple HomePod, Google Home, and Amazon Alexa were sold [23]. While there are many promising applications for such IoT devices, barriers relating to user maintenance, privacy, etc., have been reported that lead to device abandonment and ultimately less widespread use [54, 63, 136].

The applications of intelligent environments also vary across different spatial scales (see Fig. 1.3). One of the vital principles by which intelligent environments function is to digitize user activities and movements. This principle enables computing to be applied on top of a wide variety of activities in built environments as envisioned by Mark Weiser [247] in 1990

> ”The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it.” [Weiser, 1991]

In his seminal article ”Computer for the 21st century,” Mark Weiser proposed the idea of ubiquitous computing, i.e., computing will become pervasive and be all around us in a connected world. Much of his concept of ubiquitous computing was about computing melting into the background passively without demanding attention. Many of today's technologies bear a resemblance to Weiser's vision, and a considerable chunk of his vision has come to fruition. For example, today's homes and office spaces are ”smart”, and they can continuously monitor inhabitants, track their activities, and provide contextual awareness.

Pervasive smart IoT devices are ubiquitous in our built environment today and are computationally capable of controlling lights, heating, and AC. Devices also monitor whether we watch too much digital content at night, spot issues with our environments (e.g., water leakage, power failure) for home safety, amount of time we work and exercise to improve lifestyle decisions. Many of these devices are networked to transmit information, enabling computation from a central location.

Although many reasons helped realize Weiser's vision, two related ideas have significantly contributed to it. First, the idea by Feynman that computers and computing do not need to be so large [68], which directly contributed to the miniaturization of electronics and computational components that are available to us today. In his famous talk in 1960 [67], he advocated for computer scientists to think about going further with computing elements. To more succinctly capture his thought:

> ”...but there is plenty of room to make them smaller. There is nothing that I can see in physical law that says computer elements cannot be made enormously smaller than they are now. For instance, the wires should be 10 or 100 atoms in diameter, and circuits should be few thousands of angstroms across.”

Today, nanotechnology ultimately realized Feynman's vision, and billion-dollar fabrication laboratories made it possible to miniaturize electronics.

Subsequently, the second related idea that furthered ubicomp's vision was the Internet of Things (IoT), a word coined by Kevin Ashton and the idea furthered by Niel Gershenfeld [73] through ”things that think” [24]. In his pioneering article, Gershenfeld advocated for endowing everyday objects, like alarm clocks, home security, pill bottles, washing machines, etc., with the ability to connect to a network. Such a network would make it easier for connected objects to work in unison based on pre-programmed behavior set by the user. The proposed idea enables homeowners to configure their lights, switches, and everyday objects connected to the network. The ability to configure would help reduce the cost and complexity of building construction, help with home health care, and provide many applications.

Despite these early ideas, we are very far away from achieving the goal of true ubiquity and ”human aspects” (such as reducing cognitive attention, portable displays, scrap computers, etc.) of Weiser’s vision. To date, our devices are clunky, not seamlessly integrated with the environment, power-hungry, and not yet made with the most typical materials that we see around us. We need to think more creatively about how we can make genuinely ubiquitous computing devices.

In 2020, Abowd [27] argued for computational materials as an approach that needs to be further studied to complete Weiser’s vision. He advocated for the simultaneous importance of three core areas in designing computers: power, the scale of materials, and the form factor. The reasoning behind the core areas is the predicted end of Moore’s law [206], and more significantly Dennard scaling has already ended, which means that our devices will remain power-hungry.

While addressing those core concerns, we also need to simultaneously think about the context in which computational materials are deployed and the computational functionality they may enable to help users. For example, we spend about 87% of our time in the built environment, so how the built environment is ”made” is tremendously important considering that we spend a significant amount of our daily lives. The built environment is made up of infrastructure materials; therefore, it is crucial to consider the challenges and functionality involved in making them computational.

In short, in this thesis, we are interested in asking the overarching question: Can the vision of ubicomp be better realized by inventing computing devices with commonly found infrastructure materials in the built environment? If computers are omnipresent, we should better integrate them where we spend most of our time.

This thesis aims to address these challenges by proposing computational infrastructure materials for the built environment. Computational infrastructure materials enable low-power, integrated sensing, communication, and actuation in the physical infrastructure forms (e.g., buildings) for purposeful applications. Application areas of such computational infrastructure materials are smart structures with printed electronics, room-scale activity recognition structures, accessibility, interactive deployable structures for emergency disaster response settings and smart architecture, extreme low-power sustainable IoT devices, robotic construction, and much more.

1.2 Key Challenges

1.2.1 Form factor

The goal of making a computer disappear happens in two different ways – mental and physical disappearance. Although these two are interlinked, their objectives are different. The artifacts can be large with mental disappearance, but they are not perceived as computers because people discern them as interactive walls or tables. Thus, technology moves mentally into the background. On the other hand, physical disappearance

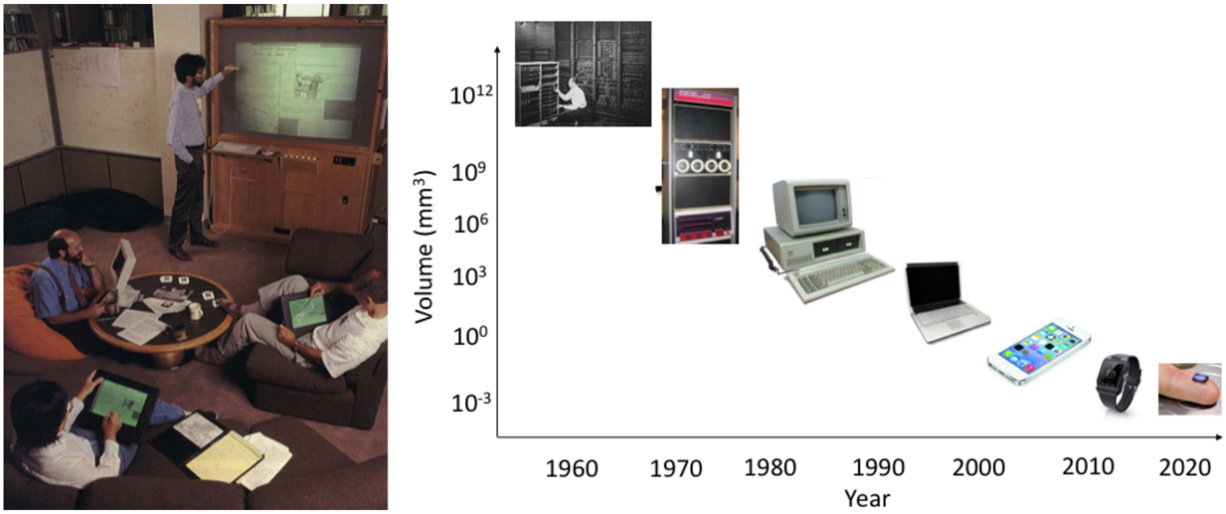


Figure 1.1: Shows a)Mark Weisers concept of ubiquitous computing where scentists at Xerox Parc work with "live boards", "pads", "active badges" and with customizable information display b) Evolution of computing device form factors

refers to the miniaturization of devices and their integration in other everyday artifacts, e.g., in clothes, so that you do not visually see them anymore.

Unfortunately, even with decades of advancement in electronics technology, the integration of computers with everyday artifacts remains a challenge. Form factors for interactive and ubiquitous devices primarily rely on conventional rigid materials and substrates. For instance, device manufacturing is heavily focused on miniaturization, and as a result, the devices we have for ubiquity are mainly – laptops, tablets, smartphones, and smartwatches in that order of miniaturization (see Fig 1.1b). To date, such device manufacturing and electronics emphasize packing the most functionality into the smallest of form factors. The critical question is if we look at the built environment scale (like walls, tables, etc., see Fig 1.3) or the materials they are made of, do the circuits and corresponding components need to be embedded in smaller form factors, or conventional materials?

Devices have mainly been underexploited in terms of the materials with which they are made. Therefore, the form factor, affordances, and functions enabled by the built environment materials have never been utilized to the fullest extent. For example, you could manufacture interactive devices with extreme flexibility, portability, extremely high mechanical strength (which can handle several thousand pounds), etc.

In we refer back to original vision, Weiser illustrates how "Pads" differ from conventional portable computers.

> "Pads differ from conventional portable computers in one crucial way. Whereas portable computers go everywhere with their owners, the pad that must be carried from place to place is a failure. Pads are intended to be "scrap com-

puters." (analogous to scrap paper) that can be grabbed and used anywhere; they have no individualized identity or importance. [...] Pads, in contrast, use a real desk. Spread many electronic pads around on the desk, just as you spread out papers. [...] Spread the many parts of the many tasks of the day out in front of you to fit both the task and the reach of your arms and eyes, rather than to fit the limitations of CRT glassblowing." [Weiser, 1991]

Today's reality is very different; ubiquitous computers, such as laptops, tablets, smartphones, and large displays, are personal, expensive (non-scrap-like), and non-shareable display devices. They rarely support the same affordances when we use paper or any other physical objects such as walls, tables, etc. More importantly, there is a minimal subset of device form factors available for use in the built environment; this, in turn, limits the set of applications enabled by novel form factors. We still use at most two or three screens and stare at them all the time to perceive information.

In this thesis, we focus on the form factor and materials with which ubicomp devices are made, particularly infrastructure materials used for the built environment, as an essential facet for engineering ubicomp devices.

1.2.2 Power & Sensing challenges in the built environment

Heavy focus on miniaturization and packaging means that devices need to be deployed in massive quantities to enable interactivity in the built environment (buildings, sidewalks, etc.) scales (see Fig. 1.3) to achieve greater coverage ([106]). This results in a dense network of sensors deployed in the built environment, leading to heavy user maintenance (if powered by batteries) and costs. Much of today's IoT devices still rely on battery power, which has two significant implications. First, there is an enormous user burden toward maintenance when IoT devices are deployed in buildings and home environments. Second, batteries have high environmental costs. By 2030, the world is projected to have more than 200 billion connected IoT devices. Assuming that each IoT device consumes 10.3 mW (BLE) of power and runs for 8 hours on a coin cell battery, this amounts to enough battery waste to fill 8 Empire State Buildings per year [30].

Moreover, when sensors are deployed, the aesthetic function of the built environment is rarely considered, leading to clunky and inconsistent integration of many sensors into the built environment. For seamless integration in smart structures, sensors must be an integral part of the manufactured structure and hidden rather than configured, externally attached, and exposed. Traditional electronics and sensing approaches do not support embedding into novel materials and making the manufacturing process more difficult. For example, cement begins in a wet and caustic form and undergoes an exothermic reaction during curing, making the embedding of electronics challenging. Similarly, when textile materials are used to fabricate structural forms, these materials need to be highly flexible and deployable (supporting expansion), therefore traiditonal rigid electronics are harder to integrate. Sensing approaches should also support harsh conditions of use in the built environment form factors such as outdoors or floors, facades, sunshades, pavements, near water, etc. Approaches must support robustness to physical environmental conditions. For instance, a concrete countertop might encounter water splashing from kitchen use, or a wall outside might experience rough weather (snow, rain, etc., as well as expansion and contraction of materials). Floor tiles might face constant impact from footsteps, or a canopy might need to support bends and twists while sensing, or objects such as bike handlebars may experience high impact forces while being used.

Finally, enabling sensorization of form factors in the built environment (walls, tables, etc.) means supporting human interaction on a larger scale. For example, if form factors such as walls need to enable sensing across large accompanying spaces such as rooms.

This thesis focuses on the power and sensing paradigms that enable smart environments to be energy efficient and materials used for the built environment to be engineered for sensing.

1.2.3 Actuation challenges in the built environment

Actuation in devices has demonstrated benefits in areas of robotics, haptics, and communication in HCI. Barring the exception of exoskeletons used for assistive technologies, right now, actuation mainly focuses on supporting human interaction at the "hand-scale". We have paid less attention to creating interactive objects at a larger scale: what we might call a "room" scale (or larger) or in a built environment.

There are many challenges when thinking about actuation in the built environment. Often, structures we see around us are built and then, often with considerable effort, retrofitted with custom actuation (e.g., automated doors/windows with proximity sensors) with rigid conventional materials. If actuators are to be deeply embedded in walls, facades, structures, etc., they must be large, support human-scale interaction, and be made with everyday materials. For example, there is a need to focus on materials with large expansion ratios and mechanisms designed to consider material properties (such as stiffness and flexibility). In this thesis work, we focus on actuation enabled as part of the built environment with unconventional materials

1.2.4 Wireless communication challenges in the built environment

Today, almost 80% of wireless communication is carried out in buildings and the built environment. Like water, gas, and electricity, wireless communication is one of the most fundamental utilities in the built environment. However, most of today's wireless communications occur via powered fixed-wall devices or through devices with batteries. Besides being power-hungry, many of today's wireless communication devices are in boxed form factors; they are far removed from materials and disparate from the form factors with which we as humans interact every day. For example, our doors, floors, ceilings, walls, etc., do not imbue any active or passive wireless functionality.

Integrating such wireless communication functionality into these built environment forms will require solving challenges in manufacturing and cost. Fortunately, the production practices of how infrastructure is built are changing. For example, newer infrastructure materials that are sustainable, pre-fabricated, and cost-effective are being adopted. This allows end-users to embed interactive wireless functionality into built environment settings more scalably. In addition to integration challenges, the additional challenge here is to figure out how to power such wireless material devices. The built environment is endowed with power sources such as natural sunlight, generated waste heat, and human kinetic energy. Although such sources of power may be intermittent, there are challenges in harvesting power, energy density, storing it, and provisioning it for human use.

This thesis focuses on wireless communication enabled by such intermittent power sources and deeper integration into infrastructure materials and their form factors.

1.2.5 Access to Digital Fabrication Machinery and Platforms

Weaving computation into a built environment means inevitability having the capability to "digitally make the built environment", i.e., having the ability to modify and instrument the built environment with fabricated objects.

Access to new digital manufacturing capabilities (especially 3D printing) has dramatically increased over the years. Today, low-cost 3D printers are available for less than $200. There are several reasons for the increased access; the first primary reason is the expiration of key early digital manufacturing patents. For instance, in the year 2009 a key 3D printing patent [21] related to fused deposition modelling expired, which led to the democratization of the technology. Second, due to advancements in computing technology, we can draw and model many designs on the screen or virtual world. With a push of a button, we can realize the digital designs as physical embodiment after computation. Moreover, approaches such as printed electronics (*e.g.,* inkjet printing, 3D printing, etc.) have demonstrated the advantages of providing low-cost, highly accessible digital electronic fabrication methods. We see advances that increase the level of customization in the printed, electronic process [232], serve a broader spectrum of users. We can create fully functional interactive devices much like the "scrap computers" envisioned by Weiser with embedded circuits and sensors with the push of a button.

While such promising technological advancements exist, there are still barriers to using digital fabrication machinery and platforms. For example, the materials with which objects are made are still pretty limited; so far, material use has been dominated by plastics on low-end digital fabrication machines. We see a wide variety of materials in the built environment, like concrete, cement, composites, plaster, wood, etc., that are largely inaccessible to average users for computer-controlled digital fabrication processes. The size of objects supported by the fabrication machines is also small. On the other hand, many of our surfaces, walls, and facades in the built environment are large-scale; hence, modifying them demands an investigation into accessible large-scale fabrication machinery. Similarly, custom tooling and software support are essential to embed interactive elements in the middle of print processes.

1.3 Computational Infrastructure Materials: Research Questions & Contributions

Taking into account the challenges outlined in the previous section, in this section, we outline key thesis research questions and a brief description of the approach, contributions, and design space enabled by the thesis.

We take a material and manufacturing-driven approach to overcome the aforementioned key challenges. We engineer interactive devices with form factors found in the built environment, and computational capabilities are embedded (See Fig 1.2) to support a wide variety of human interactions. We call our approach "computational infrastructure materials" since we work with materials in the built environments like concrete, cement, plaster, composites, wood, etc., enabling low-power, material-integrated sensing, communication, and actuation in devices manufactured in the built environment form factors.

The main contribution of this thesis is to tackle the five research questions below:

- RQ1. Formfactor: What form factors and design space do devices for the built environment enable?
- RQ2. Sensing & Power: How to enable room-scale sensing in the built environment while powering sensors in a battery-free, sustainable manner?
- RQ3. Actuation: How to enable the built environment form factors to actuate and self-deploy?
- RQ4. Communication: How can infrastructure materials be designed to communicate wirelessly with the built environment and users sustainably?
- RQ5. Access to fab machinery: What custom devices should be built to support large-scale devices and machines that work with infrastructure materials?

First, this thesis enables a wide variety of form factors. An overview is provided in Fig 1.2, for instance, walls, tables, the entire structure, facades, sidewalk surfaces, and products with structural materials like bike handlebars, golf clubs, etc., as a result of our approaches. All these interactive forms tightly integrate compute, sense, communication, and actuation functionality to be interactive. We outline the design space of the proposed computational infrastructure materials in figure 1.3; a broader design space not tackled by the thesis is also seen in the figure.

Second, this thesis offers sensing approaches for seamless form and material integration. As discussed earlier, the critical challenge here is to remain sensitive to aesthetic

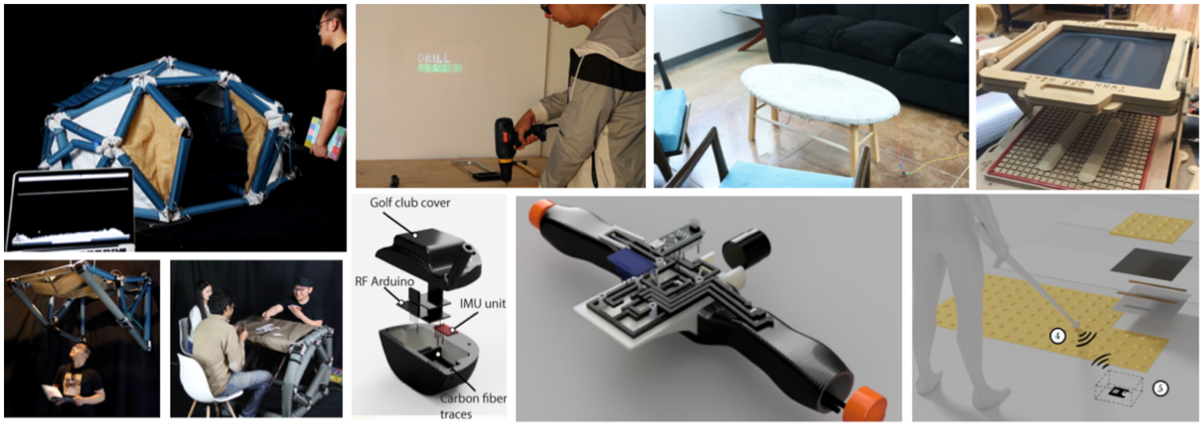


Figure 1.2: A range of built environment form factor interactive devices enabled by computational infrastructure materials

Figure 1.3: Shows the design space tackled by the computational infrastructure materials approach so far, are highlighted in green.

considerations while providing robustness for harsh conditions of use. The approaches introduced in this thesis achieve the goal of deeper form integration by modifying the properties of materials to transmit signals to support sensing. The second sensing challenge to which this thesis contributes is enabling long-range sensing while powering sensors in a battery-free, sustainable manner.

Third, our approaches look at embedding mechanisms into fabricated materials to support large-scale actuation in built environment structures (like facades, sunshades, etc.).

Fourth, his thesis contributes battery-free wireless communication capabilities in a sustainable built environment material such as wood.

Finally, the thesis contributes a range of machinery and digital fabrication processes that help users work with built environment materials like cement, plaster, textiles, etc. The introduced fabrication approach also enables users to produce interactive structures that are larger in scale while supporting the embedding of custom computational elements like sensors, actuation mechanisms, etc., during the fabrication process.

1.4 Document structure

In the following two chapters, I will review prior work and discuss my approaches to creating interactive computational materials for the built environment. In Chapter 4, I describe Optistructures, a method for manufacturing computational capabilities in room-scale physical structures such as walls, tables, furniture, etc., using a power-efficient optical approach. Common infrastructure materials (concrete, plaster, etc.) are programmatically embedded with optical fibers to provide interactive displays with room-scale sensing in structures. Further, the project demonstrates battery-free sensing (without any local power) in structures located at long ranges ($\sim$70km) from the power source. Chapter 5 describes Fiberwire, demonstrates my approach to engineering carbon-fiber composites, a structural material with inherent sensing and circuit capability. Such computational infrastructure materials enable the fabrication of a range of mechanically robust objects that can remain interactive while bearing large impact forces ($\sim$4000 lbs). Chapter 6 summarizes interactive deployable structures, a project that aims to support the creation of room-scale built environment structures like tables, canopies, and geodesic domes that can self-deploy and provide inherent sensing and actuation capabilities engineered within materials. Chapter 7 introduces computational wood, a new wood fabrication method that enables wireless sensing and interaction without batteries. Further, when objects such as dressers, door handles, input devices, etc., are manufactured with computational wood, human kinetic interaction (e.g., pulling the drawers) powers the underlying circuitry to send battery-free wireless broadcasts. Chapter 8 examines the first application of computational infrastructure materials in supporting the accessibility of non-visual navigators. The project uncovers insights from the field about how to practically deploy computational infrastructure materials to support application domain-like accessibility through multi-modal tactile guidance surfaces. Finally, in Chapter 9, we will conclude the dissertation with contributions made by this thesis and directions for future work.

Chapter 2

Related Work

Our work relates to several areas of active research in Human-Computer Interaction, Digital fabrication techniques in architecture & Civil engineering, Low-power sensing & communication, Large-scale sensing, and Material techniques for actuation. We go over each of these topics in depth.

2.1 Large-scale digital fabrication techniques

There are an array of techniques for large-scale digital fabrication. Most of these techniques are inspired by literature from architecture and fall under the following categories: (1) Additive manufacturing (AM), (2) Subtractive manufacturing & Digital Casting (3) Robotic manipulation.

2.1.1 Additive manufacturing

AM techniques for architecture focuses on layer by layer deposition of materials on a large scale. There are now many processes and technologies that have evolved with this form of manufacturing, the range of materials has expanded beyond plastics to include metals, clay, cement, composites, etc. Traditional cartesian 3D printer setups are scaled up to produce large-scale fabricated objects; this process is otherwise known as Big Area Additive Manufacturing (BAAM) [91], and it has demonstrated benefits with large-scale polymers and composites. Researchers have manufactured chassis and body of car [56]. BAAM, however, is prone to interlaminar strength issues due to the nature of 3D printing (void formation), and researchers have tried to address those issues [62]. With the vat photopolymerization technique, the curing process can be more uniform, and the process itself can be sped up to increase the pace at which objects are created [114, 230]. Photopolymerization techniques that work at larger scales are yet to be developed. Other architectural scale techniques include contour crafting [116, 266] and concrete printing, [93] which are both extrusion-based processes for AM of cementitious materials. In contour crafting, the mortar mixture (hydraulic cement) is deposited using a nozzle capable of motion along three axes. For a more thorough review of AM processes for infrastructure construction, we refer to [39]

2.1.2 Subtractive manufacturing & digital casting

Large-scale subtractive manufacturing with CNC milling is a more common form of producing meshes and inlays made out of wood, foam (EPS or expanded polystyrene), etc. These products can later be used for custom formwork, which holds and shapes concrete as it cures. For instance, the Spencer Dock bridge in Dublin [149] required more than 100 formwork inlays to be custom milled. Similar examples can be found with the o-14 tower by Reiser and Umemoto in Dubai [179] where CNC cut formwork produced unique structural facades. While many geometrical possibilities exist for such formwork, CNC milling and subtractive manufacturing of inlays tend to be slow, energy-intensive, [133] and unsustainable due to the single-use nature of the formwork components. Newer techniques examine stay-in-place formworks that use inlay components for reinforcements as well as supporting formwork. For instance, the mesh mold metal process introduced at ETHZ [85, 201], similarly knitted fabric [180] is also used for stay-in-place formwork in large scale structures. Other approaches include the digital casting framework, where temporary structures are 3D printed additively [139] using robotic arms and concrete and other cement-based composite materials are deposited.

2.1.3 Robotic manipulation

The third approach to architecture fabrication is to use robotic arms and mobile robots to support digital manufacturing like bending, folding, weaving, and which can work at large scales. For example., Gramazio and Koehler [78] fabricated building facades by extruding filament in 3D space using robotic arms. Similarly, Mataerial [2] is a project where freeform fabrication was achieved using a robotic arm to cure polymers while printing. Minibuilders [3] uses mobile robots to print along a driven path and build up the foundation footprint of buildings along that route. MIT's fiberbots [113] introduces cooperative robotic manufacturing processes that are designed for large-scale objects and structural elements using weaving and free form printing.

While these are three major paradigms in architecture, much of the focus is on form work and applying computational methods (robotics, algorithms, etc.) for creating custom formwork. Less attention is paid towards integrating functional elements like electronics or functional materials towards creating interactive structural forms that respond to humans.

2.1.4 Fabrication of passive room-Scale structures in HCI

A growing number of researchers in the HCI community and other relevant fields have started investigating how to scale up fabrication processes for larger structures for average users. One body of work looks to guide human workers to assemble structures with hand-held tools and feedback. For example, Yoshida et al. [265] guided human workers with projection mapping and hand-held dispensers that used chopsticks and glue as the primary construction material. Similarly, in the crowdsourced fabrication project [121] human workers were guided to different locations of a structure with a LED device embedded in the structure itself.

Other researchers have studied how to enable users to develop their own designs of structures, print and assemble them using desktop 3D printers. For example, Luo et al. [142] designed Chopper, an interactive system that lets users decompose a large 3D object into smaller parts so that each part fits into the printing volume of a desktop 3D printer. Trussfab [119] is a system that enables users to create their versions of trusses, print joint connectors, and assemble them using plastic bottles. More recently, and forming the important motivation for the work here, Printflatables [202] introduced machinery and design primitives for fabricating human-scale pneumatic objects as a single component.

2.1.5 Fabrication of interactive structures in HCI

Recent research in large-scale structure fabrication has ventured into supporting interactive applications. For instance, Wall++ [273] demonstrates wall treatment methods and corresponding sensing hardware to turn passive walls into context-aware structures using electric field sensing of nearby objects. TrussFormer [120] enables users to create large-scale truss-based structures that actuate. Our thesis work draws inspiration from these projects. It, however, places a greater focus on enabling the fabrication of interactive room-scale structures made with building-scale materials (*i.e.*concrete, plaster, etc.). Additionally, we show how our fabrication pipeline, embedded displays, and sensing approach create smart infrastructure for room-scale interactivity.

2.2 Large-Scale sensing approaches in built environments

2.2.1 Cameras

There are many techniques using cameras to enable sensing at scale in the built environment. The most popular techniques are by Rohrbach et al., [197], who compiled a database of cooking activities and used supervised machine learning to detect activities at scale. Similarly, more recent deep learning (convolutional neural networks) based approaches [207] have deployed computer vision at scale to track the broadest set of user activities at scale. Deep learning approaches suffer from needing extensive data; hence computer vision researchers have also worked on approaches to collect large-scale activity recognition datasets [45]. While unsupervised machine learning can be used for the detection of simple classes, it suffers from bias [229] and false positives [244]. Human-powered camera-based systems such as Zensors [126] which employs humans in the loop for labeling data and bootstrapping ML processes, have vastly improved the recognition accuracies [83] for activity detection in the built environment.

They have also made the deployment of such systems more ubiquitous and accessible for average users to set up as sensor feeds. Similarly, researchers have also used low-resolution thermal cameras to recognize human activities from black body radiation [147**?**]. Much of the research on camera-based activity recognition systems has moved into products and are started to be commercialized (for example, Ring [22] and Zensors [25]). For a more comprehensive review of camera-based techniques, please refer to [181]. The significant drawbacks of camera-based, large-scale sensing systems are (1) their effects on privacy and (2) their integration is still in the form of rigid components or electronics affecting form factors in places where they are deployed. Cameras deployed in built environments (homes, cities, etc.) have received widespread criticism due to often disclosing more identifiable information (pictures, videos, etc.) than needed [18, 205]. Often, these perceptions affect adoption and their widespread use.

2.2.2 Microphones & Accelerometers

Another common approach to sensing in a built environment is to use microphones and accelerometers as sensors. Previous research has demonstrated applications such as general interactions [127] as well as detection and/or measurement of eating [37, 209], drinking [92], brushing teeth[224], washing hands[187], falling [53, 61], gunshots [48] and much more [122]. There has been recent commercial success with such approaches too, such as Google Home, Siri, and Alexa. These products are mass consumer market smart speakers with microphones. Techniques to teach these speakers to recognize activities [256] have also been introduced. However, there are three main significant drawbacks with both (microphone & accelerator) these approaches. First, accelerometer based approaches are narrow bandwidth (limited around 5 kHz), that is, they work for specific frequencies and responses are better in those frequencies. On the other hand, microphones have a relatively wider bandwidth but are typically limited to the audible range of frequencies and by the distance to which sound waves can transmit. Other issues relating to microphones are privacy issues similar to a camera as they record human speech, which might contain sensitive information. Finally, both these approaches act as point sensing approach where multiple of them are needed to cover a wider area for sensing. More importantly, integrating & embedding these sensors into existing built environment form factors poses challenges of their own such as surviving harsh materials (cement, plaster, etc.) and their corresponding harsh use.

2.2.3 Infrastructure mediated sensing

Most related to this thesis are approaches of transforming built environment structures into sensors. This body of work examines user activities that can be detected based on signals that are propagated through the built environment. These include vibration on building floors [171], single-point sensing methods have shown how to recognize water consumption [69, 71], electrical events on power lines [175], and the movement of individuals within a building based on air pressure [176] or electrical noise [214]. More recently, a single plug-and-play device with multiple sensors has been used to detect a variety of activities within a room (a microwave being used) [128], and when placed in a network of such devices, across multiple rooms [124].

More generally, human activity recognition has been accomplished with a variety of large-area sensing techniques. Some common approaches include laser vibrometery [271], large surface sensing electronics including inkjet-printed capacitive electrodes and RF antennas [76] off-the-shelf LIDAR sensors [123], microphone-captured acoustic events [64, 129], pressure sensing mats [194], and surface vibration sensing using accelerometers and/or geophones [40, 66, 144, 151, 182].

Researchers have also examined how to scale interaction to larger-scale surfaces and infrastructure. For example, GravitySpace [42] looked at how to estimate and sense different poses of users on the floor using Fourier-transform infrared spectroscopy (FTIR) and a camera located below the floor. Paradiso et al. [172] used a scanned laser rangefinder operating parallel to a wall's surface to detect hand touches. BaseLase [153] provided an interactive context+focus laser projected floor that users can interact with using cameras to track users' positions and poses.

Other sensing approaches related to infrastructure involve using a contact microphone with room-scale objects such as windows [173], or a ping-pong table [100] to perform acoustic time of arrival sensing. More recently, Wall++ [274] looked at how to allow walls to become smart infrastructure and perform context-aware sensing by electric field tomography near a wall augmented with a painted on antenna array, as well as sensing of electromagnetic noise in a space.

2.3 No Power and low-power wireless sensing

Low power or no power wireless sensing has emerged as a sustainable and maintenance-free paradigm for tracking user activities in room-scale built environment settings. There are many ways to implement such wireless activity recognition techniques. Among these existing methods, there are three main ways to support no power and low-power wireless sensing. These are: passive (completely no power), semi-passive (energy harvested), and active radio techniques (powered). We go over relevant work in each of these domains.

2.3.1 Passive backscatter techniques

To empower smart, everyday connected objects to interact, researchers have used radio frequency identification (RFID) techniques. RFID techniques use the power from specialized readers emitting radio waves to power RF chips to sense, compute and transmit information onto signals (backscatter reflections) back to the readers. RFID passive techniques are now developed into general-purpose computing platform connected with sensors [200]., and used for activity detection in wide range of settings

[44, 131, 178, 210]. Similarly, another body of work has also looked into fabricating entire objects that reflect signals passively for sensing activities. For instance, [132] demonstrated paper-based objects and mechanisms to detect activities. Arora et al. [32], [33] used paper microphones to transmit audio passively, Iyer et al. [101, 102] used 3D printed mechanisms to build full objects that reflect and track the activities of an end-user. These techniques, however, suffer from rich multipath effects indoors, with multiple walls coming in between them. The sensing range is typically less than 15m and there is line of sight operation restrictions between reader and tags. Hence, these are not suitable for interactive devices that operate at a built environment scale (buildings, sidewalks, etc.)

2.3.2 Semi-passive backscatter techniques

Semi-passive backscatter techniques rely on battery or energy harvested power to control the process by which they reflect information on ambient carrier waves in the environment. Several systems look at using such mechanisms for applications in agriculture [57, 58] or to enable a general-purpose sensing platform with harvested power [189]. These applications have also enabled capabilities such as battery-free cellphones [222], battery-free cameras[154] that all work with harvested power and energy storage. While most of these applications of semi-passive techniques are interesting at shorter ranges (<15m), none of these techniques support distances beyond that. Some recent work looked at supporting longer-range backscatter using energy harvesting. For instance, LoRa Backscatter technique [221] supports up to 237.5m of backscattering from the reader. Similarly, reflection amplifiers such as tunnel diodes can be used to power backscatter sensors that work at room-scale [235] and even be extended up to city-scale (1km-2km) range [184]. The last set of backscatter work that operates at city-scale and room/building scale is relevant to this thesis work, as we aim to support built environment scales.

2.3.3 Active radio techniques

Active radio technique methods support the generation of entire carrier waves separately and using them to detect/sense phenomena happening from afar with received carrier waves. Built environments are surrounded by purposefully transmitting active WiFi signals that continuously transmit and receive data between several devices. A body of work has examined how to leverage WiFi signals for monitoring heart rate [29], respiration [240, 269], emotion [276], liquids [193], etc. There is also an extensive body of work on using ambient WiFi signals for indoor localization and tracking [134, 223, 242]. All this work can be broadly categorized as device-based or device-free (not requiring the end-user to carry something). Many of these techniques focus on human activities rather than instrumented objects or materials in the built environment. Finally researchers have also used active radar for user identification and localization [234], posture sensing [28], and object identification [263]. There is a comprehensive survey of radar-based techniques [135] for more detailed analysis. WiFi and radar-based active radio techniques also work within a 15m range and suffer from rich multipath effects. Most active radio techniques suffer from high power consumption (tens of milliwatts) and, often in the built environment, carrier waves may not reach all the sensing locations. Hence recent set of techniques have also looked at ambient carrier-less transmission techniques (ACLT) [275], [235]. While these new low-power ACLT radio techniques show exciting possibilities, there is less focus on fabricating and integrating several components of radio transmission. These include systems like antennae, substrate materials in novel form factors (like paper, flexible materials, etc.) into fully fabricated objects that work at built environment scale. This thesis focuses on contributions in the low power space that tightly integrates novel form factors with several compute and radio transmission elements (like electronics, antennae, sensors, etc.).

2.4 Digital sensor and actuation fabrication

A wide range of literature in HCI has looked at how to enable digital fabrication of sensors and electronic circuits. In order to tightly integrate with form factor, a review of the literature is essential to understand the techniques involved.

2.4.1 Digital sensor fabrication techniques

As only a few examples: Midas [203] introduced a software and hardware toolkit to fabricate custom touch sensors using copper tape and a vinyl cutter. Instant Inkjet Circuits [112] demonstrated the capability of printing circuits on an off-the-shelf inkjet printer by modifying the printer to deposit silver ink and thermally sinter them to form circuits. Circuit stickers [90] introduced a method for attaching electrical circuits to large contact area stickers that are flexible. PaperPulse [188] used an inkjet technique to lay circuit designs on paper and allow designers to customize and assemble them quickly to form widgets like slider, radio button, etc. on paper. Finally, Printem [250] introduces a new technique to create one-off printed circuit boards with copper by selective curing UV adhesive stacked on top of copper. Capricate [204] introduced a fabrication pipeline to design and 3D print capacitive touch sensors.

Other work in the HCI community has fabricated flexible sensors using conductive inks embedded into deformable 3D printed objects [36] or absorbed into soft materials like sponges [157]. Another approach examines impregnating elastomers with carbon particles to create piezoresistive sensors [264]. PneUI [260] demonstrates how sensing materials like liquid metal and conductive foil can be embedded into soft pneumatically actuated composites to create sensors in PDMS (commonly referred to as Silicone Rubber) at hand scale. Similarly, Aeromorph [170] examines how changes in air pressure can be sensed in heat-sealed inflatable objects. In the domain of textiles, researchers have explored embedding conductive textiles into other soft materials (e.g., fabrics) to create sensing opportunities on and around the body [130, 183, 237].

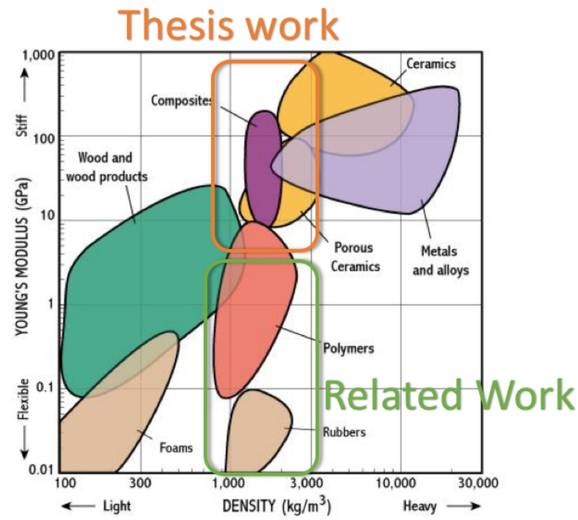


Figure 2.1: Shows the focus of digital sensor fabrication techniques for this thesis

Broadly, these techniques utilize 3D printing [12, 204, 239], vinyl/laser cutting [80, 107, 146, 257] or inkjet printing [50, 112, 115, 165]. Others fabrication techniques including chemical etching [89], screen printing [140, 161, 246, 254, 270], silicon mold casting [155, 245, 248], spraying [249, 272], and free hand drawing [185, 199] have been used to create various types of sensors [77, 111, 163, 232], antennas [132], displays [164], and mobile device touch screen extensions [110]

However, all these approaches rely on materials like paper, plastic, etc., are hence limited to printing substrates that are not structurally strong and are also limited by printing dimensions. One notable exception is [236] which describes several sensors assembled with the help of 3D printed metal parts (but not printed in-situ). More recent work has looked into investigating the versatility of embedding circuitry into a wide variety of surfaces [81], however, this also has some processing limitations, such as the need to dip the augmented object in a water tank. A more recent technique such as SilverTape [49] uses a dry transfer method that does not need to dip in a water tank.

Our focus in this thesis is complementary to the existing techniques. We focus on digital fabrication of sensors on the built environment materials (cement, composites, etc.) suitable for built environment form factors that are typically large area and act as load/impact bearing structures like walls, tables, canopies, etc. There are many techniques from civil and architectural engineering domains that are relevant. Examples include research by Soliman et al. [211] that focuses on electrifying cement with mixing of carbon nano black, embedding robust optical sensors in concrete and engineered wood buildings [47], composite aircraft wing monitoring [108, 220], and monitoring loads on wind energy turbine blades [34]. Similarly, in working with composite materials, which are mechanically strong, researchers have looked at carbon fiber-based ball-grid array interconnects (Yuliang et al [60]) and investigated how these novel interconnects can be interfaced with conventional circuitry. Lipka et al. [137] utilized the high surface area of carbon fibers to fabricate electrochemical capacitors. To increase the performance of the contact area in potentiometers, a carbon fiber-based design [212] [138] has been explored for sliding contact. Electromagnetic (EM) applications of conventionally produced carbon fiber composite materials have also been studied, including fabrication of dipole antennas [195] microstrip antennas [35] and electromagnetic absorbers [159]. The key ingredient to enable the possibility of using carbon fiber in electrical and EM applications is the conductivity and shielding effectiveness of fibers, which has been well-documented [65]. The electrical resistivity of carbon fibers can range from 10 ohm-cm, depending on the number of fibers per unit area and different treatment procedures used. In most electrical applications, the epoxy coating is removed to expose the raw carbon fibers. For example, Jeon et al. [104] showed that the contact resistance of carbon fiber composites could be brought down to 0.3 ohms by graining and removing epoxy, then depositing silver.

While many of these techniques exist in conventional engineering domains, the ability to programmatically lay down functionally materials (carbon fiber, optical fiber, silver ink, etc.) with 3D printing [8] or laminating [10] has opened up possibilities for creating fully functional built environment form factor devices with embedded circuitry and sensors. This thesis focuses on that possibility by looking at digital fabrication processes, printers, and methods for enabling computational building materials.

2.4.2 Digital fabrication of actuators in HCI

Recently, a wide variety of HCI researchers have started looking at leveraging mechanical and material properties to enable designers to fabricate various actuators in interactive devices. Metamaterial Mechanisms[97] investigates how to design the internal microstructure of an object computationally in order to achieve a desired output mechanical movement. In follow-up work, digital mechanical metamaterials [98] investigated how to fabricate simple non-electronic computational objects using a bi-stable spring mechanism for signal propagation and actuation. Cillia [168] presents a novel method to fabricate micron-scale hair-like structures using Stereolithography (SLA) onto a range of geometries that can later be utilized for both passive actuation. Similarly, Yao et al. [262] introduced biologic, a system that lets designers embed nano-scale bio actuators using bacteria that responds to humidity. Other shape actuation materials introduced in HCI include bi-strip thermoplastic material [88], 3D printed 4D actuators [31], 3D printed paper actuators [238], pneumatic driven shape-changing interfaces [167, 169, 259], biological materials [243, 261] and digital materials enabled by electro-magnetic motors [70, 156]

While these advances are helpful for actuation in hand-scale interactive devices, many approaches have not looked at room-scale or built environment scale actuation. Much inspirational research from architecture has looked at larger scale actuation. There are a few, such as the Muscle Tower project [166], which introduced a tall, open structural tower made with aluminum and pneumatic muscles that reacts to a passer-by as they lean and move towards people. Dressroom [233] is another project that responds to the location and position of a person in a room and changes its output across the structural form (fabric) based on position. The Open Columns and Exobuildings projects look at actuating columns or structural support based on Co2 levels or users' physiological data. These works convert data into physical representations in architectural spaces. Many mechanical actuators in architectural forms like [118, 225] act as large-scale general-purpose shape-changing information displays. This thesis builds and compliments these approaches by focusing on integrating actuation into materials more directly and using energy sources from the built environment for actuation.

Chapter 3

My Approach

This chapter summarizes the four fundamental approaches used in this thesis to enable computational infrastructure materials to fabricate interactive devices entirely with built environment form factors. First, we look at form factors widely available in the built environment today, the materials with which they are made, and what novel interactive device functionality can be enabled by tightly coupling material function with computational function. Second, our approach looks at using unconventional nonsilicon based analog approaches that are: a) more energy efficient for sensing, b) are amenable for better material integration, and c) provide better sensing range. Third, we look at innovation in digital fabrication machinery and the underlying material processes needed to enable the vision of computational infrastructure materials. Finally, we look at actuation approaches that are interesting and better suited for built environment form factors.

3.1 Functional interactive objects with built environment form factors

Interactive structural forms can enable completely novel computational capabilities when tightly integrated with material capabilities. In fig. 1.2, we see a range of artifacts from the built environment that are instrumented with computational capabilities. Here, we list the capabilities enabled with such form factors.

Mechanical strength (cement, composites): Typically, structures in the built environment are load bearing and can support a few thousand pounds of force. Structural materials of such extremely high mechanical strength can be engineered to create objects (walls, bike handlebar, golf club, tables, etc.) that can withstand impact forces on the order of thousands of pounds ($\sim$ 4000 lbs) and remain interactive [216].

Embedding light pipes for displays and interaction: Large surfaces such as walls and tables (see fig. 3.1), made with structural materials, can be instrumented with light

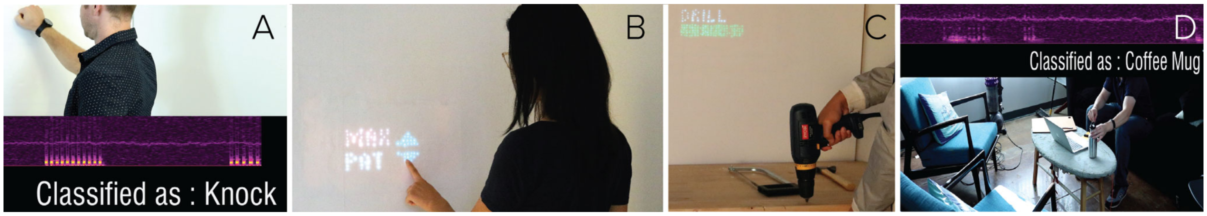


Figure 3.1: Embedded fiber optic input sensors and displays can bring interactive capabilities to room scale objects.

pipes and therefore can be used as displays and for interaction.

Sensing across large areas in the built environment: Large surfaces such as walls, and tables (see fig. 3.1) made with structural materials that span multiple rooms and the building in the built environment could be turned into sensing surfaces and repurposed as interactive devices [218].

Portability, deployability, and interactive actuation: Structural forms designed for a) portability, i.e., the ability to move large-scale objects from one place to another, b) deployability, i.e., the ability to become available on-demand, and finally, c) actuation of large-scale structural forms that respond to human interaction [217].

Harvesting human kinetic action for battery-free sensing: Human kinetic actions are pervasive in the built environment, such as walking on the floor, turning faucets, turning doorknobs, pulling kitchen drawers, refrigerator doors, kitchen cabinets, etc. These structural form factors in the built environment can be manufactured with cheap, low-cost computational materials that harvest energy and sense our actions to enable battery-free sustainable interactions.

3.2 Optical compute, material sensing and low-power analog wireless approaches

My second approach relates to thinking about new computation, and sensing paradigms that are non silicon (photonic or unconventional semiconductors) that are more energy efficient [14, 258], and are based in the analog domain and are more suited to deeper integration with infrastructure materials and the built environment. There are mainly two reasons for considering such approaches. When we think of built environment scales, an enormous number of sensors need to be deployed to make such environments interactive. Therefore, the energy required to run and maintain such devices increases dramatically. By thinking of more energy-efficient techniques where thousands of sensors can operate sustainably, we could make it a reality to realize interactivity at a built environment scale.

First, a promising avenue is to look at optical sensing methods; with Optistructures [218], Bragg grating sensors could be deployed up to 70 km from a power source and

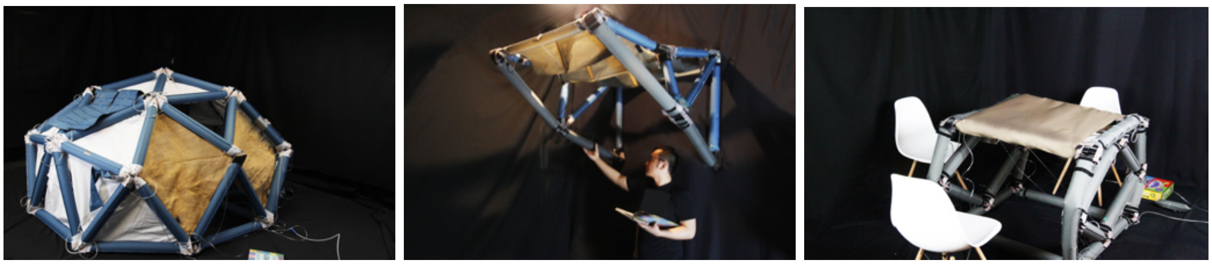


Figure 3.2: (a) A geodesic dome that deploys itself upon inflation and has embedded actuation and acoustic sensing to open its doors and raise its windows; (b) a canopy with a controllable venetian blind via capacitive sensing; (c) a portable table inflated on-demand via a pressure sensitive control. All of these structures have embedded actuation and sensing that support a range of interactions (e.g., a user performs a knock gesture on the dome's door and the door swings open).

run without batteries. Multitudes of such sensors (100s) could be multiplexed on a single optical fiber and run for as long as the structure lives. This approach also has the additional advantage of being deeply integrated with materials and form factors to survive harsh embedding and use conditions. Although the power source and interferometry performed at the end point of the optical fiber are currently bulky, there are exciting and promising results [19] that are looking at chip-scale interferometric techniques for energy-efficient photonic approaches. These photonics-based approaches have shown benefits even on the transatlantic scale [267].

Second, to tightly integrate sensors with the form factor, one approach could be to modify materials to act as sensors and transducers. For instance, the material used could be optimized for higher conductivity or act as transducers to conduct vibrations or ultrasonic waves. In both the Fiberwire [215] & deployable structures [217], we looked at exploiting existing material structures to enable sensing. In the case of Fiberwire, we modified the surface morphology of carbon-fiber composite materials to enable them to conduct electrical signals with low loss. Similarly, in deployable structures, we enabled flexible truss materials of the inflatable structures to act as a transducer to conduct ultrasonic waves perturbed by human interaction. Finally, with Optistructures [218] we looked at casting sensors into rigid materials that can act as transducers to transmit vibrations to the sensor.

Third, we enable ultra-low-power long-range active wireless interaction techniques using tunnel diodes. Tunnel diodes are attractive nonsilicon diodes (GaAs or Ge) that demonstrate quantum tunneling effect and can be exploited for creating active high-frequency transmission circuitry. Tunnel diodes tend to operate at an ultra-low power budget ($\sim \mu$watts) due to the use of GaAs, which are functional III-V semiconductors that have six times more electron mobility than silicon and therefore have more significant implications for the future of energy-efficient computing [17, 231, 258] with optical and RF chips. We use these tunnel diode transmitters in our work on the computational wood Chapter 7, where we introduce a new wood fabrication method to embed

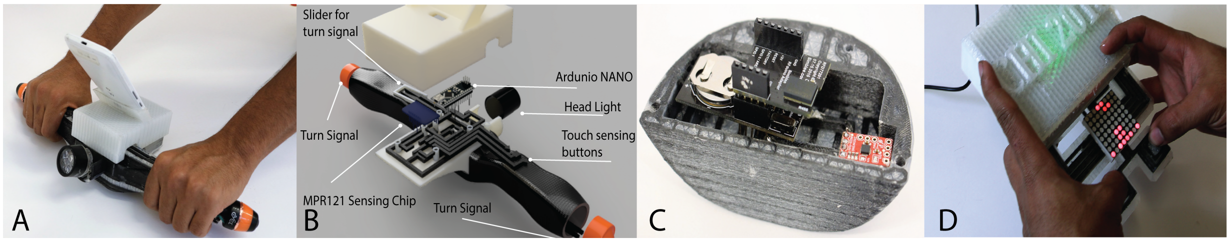


Figure 3.3: FiberWire introduces interactive devices with embedded multilayer carbon-fiber circuits within mechanically strong objects. a) shows an interactive bike handlebar with embedded circuitry and controls for phone and turn signals b) shows close up (rendered) view of its interior interactive controls and circuits c) shows the bottom face of a golf club with an embedded IMU board for interactive stroke feedback d) shows an interactive game controller with a multilayer carbon fiber circuit and tactile buttons

tunnel diodes between layers of wood. Furthermore, when objects such as dressers, door handles, input devices, etc. are manufactured with computational wood, human kinetic interaction (e.g., pulling the drawers) powers the underlying embedded tunnel diodes to send battery-free wireless broadcasts at a long built environment range ($\sim$ 300 feet).

3.3 Digital fabrication machinery for "making" the built environment

To enable the built environment form factors, we need fabrication machinery to work with built environment materials and manufacture devices with fully integrated functionality. Today, with advances in 3D printing, material science & much digital fabrication technology, we can create custom devices with novel form factors and materials. However, the space of materials with which we can work is still limited, e.g., primarily plastics on low-end printers. Average users still do not have access to machinery and domain knowledge to work with infrastructure materials such as Concrete, Carbon fiber Composites, Cementitious Composites, Plaster, Wood, Textiles, etc. Finally, the scale of fabrication also remains a challenge.

In this thesis, we present several types of fabrication machinery. In deployable structures [217], we built a custom 6 by 2 foot truss printer that enables the printing of truss members. This printer is equipped with a soldering iron that seals fabrics to create inflatable objects. With Optistructures [218], we created a custom optical extrusion device that operates in sync with large-scale subtractive manufacturing machinery (CNC mill) to embed optical fibers in bespoke inlay shapes for casting cementitious composites. In Fiberwire [215] we present a fabrication platform that combines composite extrusion, laser etching, and silver ink deposition on carbon fiber composites to conduct electrical signals. These projects demonstrate the need to build custom tools and devices that can deposit functional materials (silver ink, optical fiber, etc.) in the middle of the fabrication process to fabricate interactive devices entirely. We hope to widen access to digital fabrication technology and working materials through these devices. Further exploration of deposition in functional inks, colloids, slurry, fibers, wood-based materials, etc., may enable more comprehensive fabrication machinery for the built environment.

Another vital consideration for manufacturing costs; When working to create a batch of devices, it is essential to look at methods that support batch manufacturing. For instance, in Navtiles [219] we present making one-off molds with 3D printing and using mass manufacturing processes such as vacuum forming for the rapid creation of low-cost tiles. The second approach to thinking about this paradigm is in terms of materials used for building devices; functionalizing bulk materials like Portland cement, which costs 4 cents a pound, can enable cheaper, larger-scale built environment interactive devices.

3.4 Material based actuation approaches for the built environment

Actuation of built environment forms is challenging owing to their size and energy requirements. This thesis examines material approaches that can enable actuation on a large scale. Specifically, we look at materials used in space structures [86] like flexible pneumatic fabrics with prestressed patterns to enable actuation at a larger scale. We explore a range of techniques, and design primitives that support the creation of custom actuated large-scale objects (see fig. 3.2)

Chapter 4

Optistructures

4.1 Introduction

We are surrounded by structures that are purposefully built and provide utility to habitation and living. Structures like walls, tables, beams, etc. span large surface areas and they remain ubiquitous in various walks of life. Most structures serve a useful function of providing and organizing spaces and yet, these structures to date typically remain passive without offering any interactivity or inherent computational abilities. Moreover, the primary goals involved in design and engineering of structures have mainly focused on building and material considerations such as strength, stability, surface characteristics, etc. rather than interactivity or augmentation with computation. As a result, the manufacturing processes for structural components has remained catered towards passiveness.

With the recent advances in computationally-driven manufacturing such as 3D printing [5, 11], printed electronics [278] or hybrid manufacturing (additive + subtractive) [6] we are offered increasing opportunities for designing and manipulating structures from micro to macro scale. Some notable projects such as printed optics [253], metamaterial mechanisms [96, 99], printed composites [216] have utilized such advances for manipulating optical, electrical, and mechanical properties to print multi-functional interactive devices. However, many of these approaches work at what might be called "hand-scale" rather than larger "room-scale" components.

In this chapter, our main goal is to leverage advances in fabrication tools and sensing technology to enable interactivity in the built environments at a larger, and previously less examined, scale. We do this by creating functional structures that are interactive at room scale. To this end, we introduce a computer controlled manufacturing process supporting the construction of cast interactive objects – objects made from a liquid or paste that are solidified in a mold. This is supported by a custom modified CNC machine which can both mill custom molds for casting, and insert optical fibers though the surface and within these molds. This process allows ordinary looking objects made from a wide range of cast-able materials to be constructed with interactive capabilities implemented with embedded optical fibers. These optical fibers can both provide input as well as visual feedback (by delivering light to the surface of the object). Input is implemented using *Fiber Bragg Grating* (FBG) optical sensors which we custom configure into very sensitive vibration sensors. Multiple sensors can be integrated into, or placed in line with, a single optical fiber embedded within an object. Further, they embed only passive components (no electronics) within the material, require no internal power to operate, and can all be interrogated from a single point (the end of the fiber) using a laser-based device. Our tests show these sensors to be extremely sensitive, with an ability to detect and classify both direct interactions such as tapping, knocking, swiping, etc., as well as more subtle actions such as walking nearby or moving a chair across the floor.

Our interactive structures can be manufactured with low-cost, strong, building scale composite materials such as concrete, plaster, polymer resins, composite materials like those used to create faux granite counter tops, bio-fiber composites, etc. These materials are already widely used and readily available in home improvement stores. Our process can be used to manufacture complete objects, or our structures can be post-processed into building blocks or other components, and integrated into existing infrastructure such as walls and living spaces, providing interactivity to our surroundings. Combined together, our manufacturing process, software and hardware pipeline, sensor designs, and machine learning activity classification enable rich interactions with smart infrastructure at a room scale.

In this chapter, our work described here makes the following contributions:

- Mold and cast methods for fabricating room-scale interactive structures
- A custom fabrication device for both mold creation and computer controlled fiber optic embedding as needed to support displays and sensors.
- A technique for using embedded fiber-Bragg grating optical sensors to detect room-scale activities
- Experimental evaluation of the usable range and configuration of fiber optic sensors
- User validation of various interactions on our fabricated room-scale interactive structure prototypes

In the sections that follow, we will describe our novel fabrication and sensing approach in more detail. First, we will provide details of the sensing requirements to enable the fabrication of interactive structures (Section 4.2) and the fabrication process itself (Section 4.3). We will then turn to technical evaluations of the performance of our system with respect to casted materials, distance sensitivity, and with respect to other common vibration sensing modalities in Section 4.5. Next, we evaluate the performance of our with example applications on our two *room scale* prototypes considering a variety of common human activities and across multiple different users in Section 4.6 Finally, we conclude with discussions and future work.

4.2 Sensing Requirements

Sensing at room-scale through structures can be enabled by various types of sensors such as a high frame-rate accelerometers, surface microphones, etc. In addition to excellent sensing performance when compared to existing sensors (see Figure 4.6), our sensing approach offers significant advantages for the design and manufacturing of room-scale interactive structures. Our requirement rationale for FBG sensors is as follows:

R1. Conditions of human use: Typical use of structures is in harsh conditions such as outdoors or floors, pavements, near water, etc. For instance, a concrete counter-top might encounter water splashing from kitchen use or a wall outside might experience rough weather (snow, rain, etc. as well as expansion and contraction of materials) or floors involve the movement of items and constant impact from footsteps. Simplicity and robustness to physical environmental conditions is critical in these settings. Embedding fiber optic sensors is known to work well [94, 277] for such rough conditions, while other powered electronic sensors (such as high FPS accelerometers or microphones, etc.), are sensitive to the presence of water and not as durable for high traffic use. Moreover, in environments like workshops where there is extensive use of power tools, immunity to EM fields is a necessity that FBG offers by being optical.

R2. Cabling Labor: Enabling large-scale interactivity between sections of structures in multiple rooms also requires multiple high FPS accelerometers or other sensors to be placed. However, this requires inordinate amount of cabling labor (if wired) especially if they span across large areas. As seen in aerospace [1], where a single fiber optic cable (with many FBG sensors) has replaced bulky cables and enclosures of traditional sensors (strain gauges) in large-scale structures.

R3. Power: If wireless sensors are deployed (across rooms) they require maintenance by users such as replacing batteries. Whereas we can place multiple FBGs on a single optical fiber and they do not need to be supplied with electrical power. We note that research [95] indicates that sensing can occur on single fibers even as long as 75km without additional amplification. Hence FBG can stay in place for years without requiring any additional power or maintenance.

R4. Design and Manufacturing: Finally, for seamless integration in smart building scenarios, sensors need to be an integral part of the manufactured structure and hidden, rather than things that are configured, attached externally, and exposed. Traditional electronics may not survive embedding during the manufacturing process. For instance, cement begins in a wet and caustic form and undergoes an exothermic reaction during curing, making embedded electronics challenging.

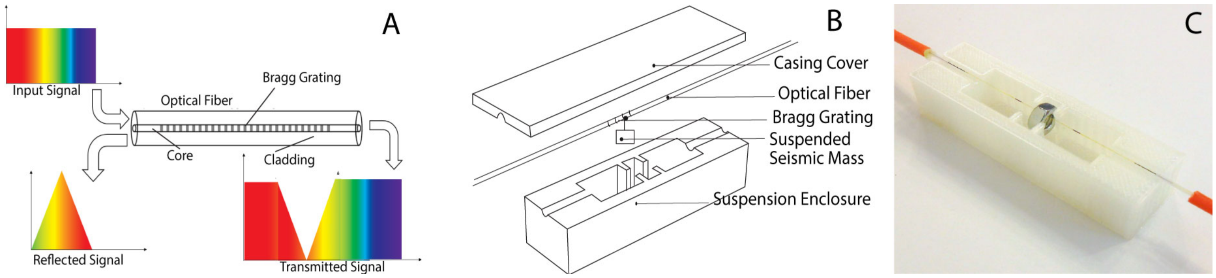


Figure 4.1: Fiber-Bragg Grating Optical Sensing and hardware. The Fiber-Bragg Grating Optical Sensor uses Bragg gratings on an optical fiber to reflect different amounts of light based on an input signal (A). The input signal is captured on a vibration transducer that houses the optical fiber (B and C).

To summarize, we derived our choice of the sensor not only due to their excellent sensing performance, but also as a consequence of the manufacturing process. One that can survive the harsh conditions of use, that can span to large surfaces without requiring power or extra cabling labor, and are immune to EM fields.

4.3 Fiber Bragg Gratings as Sensors

4.3.1 Theory of Operation

We utilize optical fibers with Bragg gratings for sensing activity and to provide interaction support around our structures. Bragg gratings are usually located inside an optical fiber and they selectively reflect light at a specific wavelength when presented with a broadband or swept frequency light source (Figure 4.1). This is done using a series of lines laser etched across the core of the optical fiber at a specific spacing. These lines create variations in the refractive index of the fiber core and result in a wavelength specific dielectric mirror. The *grating period* (distance between the gratings) in these fibers determines the wavelength of the light reflected back. When the fiber is minutely stretched (*strained*), this results in a change in the grating period, hence a change in wavelength of the reflected light. By tracking these changes in wavelength, FBGs can sense strain and can be highly sensitive with a gauge factor of 1.2 picometers of wavelength shift per microstrain (or 0.012 microns of wavelength shift per 1% strain).

By using FBGs with different periods many sensors can be multiplexed along a single optical fiber. Since each FBG can have a unique wavelength at which it reflects light, the strain occurring at each FBG can be tracked independently. Theoretically, we can multiplex nearly 100 FBG sensors in single optical fiber extending the sensing range to tens of km with no power required at the sensors themselves. Hence these qualities of the sensor lend well to our purpose of enabling room-scale interactivity.

4.3.2 Sensing and Interrogation

We use an SM130 Optical Interrogator [148] to sense the wavelength shifts in FBG when subjected to strain. Optical interrogators work by using a swept frequency laser source that passes light into the fibers and then examining the magnitude of reflected light at various frequencies.

FBG's are typically fabricated by using a femtosecond laser source [13]. The machinery to fabricate FBG is expensive, however there are a wide variety of companies which sell ready-made FBGs with pre-defined wavelengths. We use off the shelf FBG fiber costing around $30 each from Micron Optics [15] and a used laboratory-grade interrogator which costs around $800. However these devices are relatively simple in nature and with a larger market adoption, the costs of of both the FBGs and interrogator could be substantially lower (and low-cost interrogators have already been described in the literature [228]) and recent efforts point to development of new interferometer that works on a chip [14, 19].

4.3.3 Vibration Transducers

We chose FBG sensors because of their very high sensitivity and resilience to moisture, as well as to the higher temperatures and strain induced during fabrication as part of the curing process of some materials. Typically, FBG sensors are used to monitor strain and temperature for instrumented objects [109], but we have adapted these sensors for use as vibration sensors. By detecting vibration in a highly sensitive way, we can detect (and eventually classify) a range of interactively relevant human actions on or near cast materials.

To convert FBG sensors to vibration transducers we attach a small, known seismic mass (8g) to the fiber optic cable between sets of gratings in the cable. The mass was chosen based on the maximum weight the tensioned fiber can support without tearing apart. We have developed a small 3D printed enclosure box (Figure 4.1 B and C) to house the fiber-optic sensor and suspended mass. This allows the FBG augmented fibers to pass through either end, with a cavity in the center for placing the suspended mass. By casting the enclosure directly into the material, we create a bond between the material itself and the enclosure, which ensures that when the material vibrates, these vibrations are reliably transmitted to the seismic mass. When the mass vibrates, it induces a strain in the gratings which is recorded as a change in the wavelength of reflection for the FBGs as seen by the interrogator. This stream of strain values corresponding to vibrations are then used for activity classification.

4.3.4 Activity Recognition Feature Extraction & Classification

The FBG sensor measures the magnitude of vibrations occurring on the vibration transducer embedded in our cast structure. We sample raw signals at 1kHz, segmented using a sliding window of 512 samples. Next, we apply a Fast Fourier Transform on the

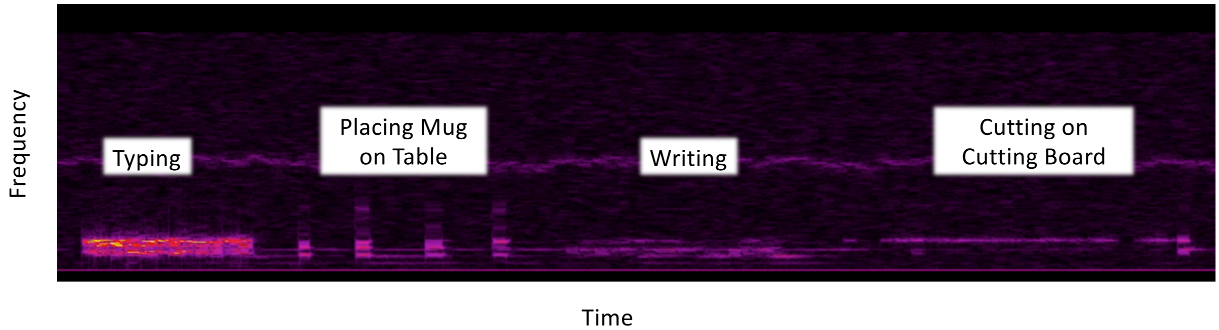


Figure 4.2: Spectrogram showing the vibration response variation for different activities on an instrumented table. Color variations represent changes in intensity/magnitude.

windowed signal and we extract features from the resulting spectrum. These features include: the magnitude of each frequency band (in the single-sided spectrum); the first and second derivative of the spectrum; the magnitude for the octave and one-third octave bands; and lastly, statistical measures of the spectral bands (min, max, range, mean, standard deviation, and root-mean-squared).

Figure 4.2 shows a series of different activities (*e.g.*typing on a laptop and writing) and their associated raw spectral content. Note the variations in the duration, frequency bands, and amplitudes (intensity of color) for each of the activities. For classification of activities and various user interactions around a cast structure, we use a Support Vector Machine (SMO-SVM, linear kernel) with default parameters (although other models e.g., boosted trees or dense networks are compatible with our sensors). Due to the variations in materials, environmental conditions, and end-use (i.e., applications), we expect that the system will require an initial calibration to train the activity classifier when first installed. Based on our preliminary studies, we have observed that this calibration can be accomplished in just a few minutes.

4.4 Fabricating an Interactive Structure

In this section, we consider details of our fabrication approach for creating an interactive structure. The steps of this process are shown for an example object which we will describe later in Figure 4.3. For this example we made use of a layered mold consisting of a flat base layer (silver) with CNC milled layers stacked over it (Figure 4.3A). Figure 4.3B and C show our custom fiber insertion mechanism and the process of inserting fibers in the base layer of the mold. Upon completing injection of display fibers, the mold is filled with concrete (and legs for a table) as well as an FBG sensor to produce the final product (Figure 4.3D, E, and F, respectively).

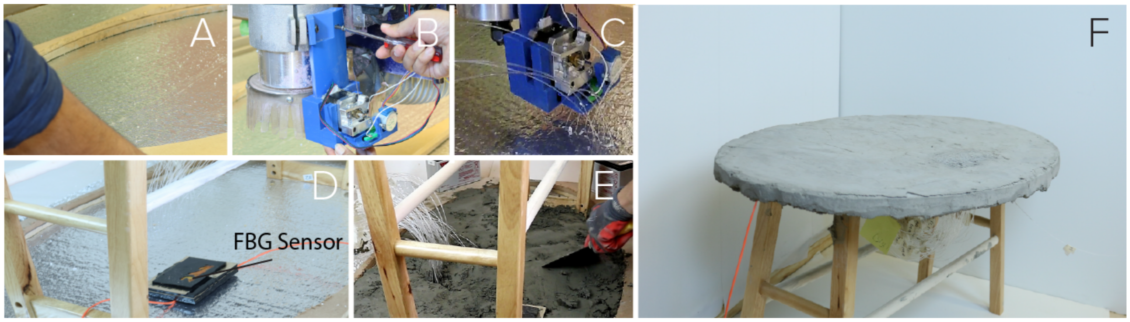


Figure 4.3: Fabrication Process for Active Cement Table including milling a mold using a CNC mill (A); attaching the fiber insertion hardware to the mill (B); inserting the optical fibers (C); placing the FBG Sensor (D) into the mold; casting cement into the mold (E); and the finished table (F).

4.4.1 Fiber Insertion Hardware

As shown in Figure 4.4, the mechanical design of our custom fiber insertion mechanism consists of a custom-designed 3D printed housing containing two stepper motors. The larger (NEMA17) motor grips the fiber to be inserted with a pinch roller in order to push it into the mold. This drive mechanism is the same as typically used to drive plastic filament into the hot end of a consumer grade FDM 3D printer extruder, and similarly uses an A4988 stepper driver[1]. We use 1mm diameter CHINLY PMMA Optical Fibers[2] in our fabrication process. Fiber injection occurs from 4mm above the mold surface and fiber is pushed into the mold at 8mm/s. Typically about 65mm of fiber is left above the injection point to provide a connection point for light insertion.

A second smaller (28BYJ-48) stepper motor (with a ULN2003 driver board) is used to actuate a cutting mechanism using a heated nichrome wire. The motor moves the hot cutting wire forward and back through the inserted fiber using a small rack and pinion mechanism.

Software

To partially support our hardware mechanism, we developed a simple web-based design tool that supports creating fiber optic display inlays on flat mold surfaces as seen in Figure 4.4 C. The tool allows a user to load a Scalable Vector Graphics (SVG) file, and/or manually draw shapes and patterns. These input shapes are converted to a series of points which fill the shape and can then be used for the hardware's fiber insertion procedure.

The spacing of the fibers can be interactively adjusted to ensure the desired display resolution is obtained before fabrication. Once the desired design is achieved, the

[1] https://www.pololu.com/product/1182
[2] https://www.amazon.com/gp/product/B073SML3TY/

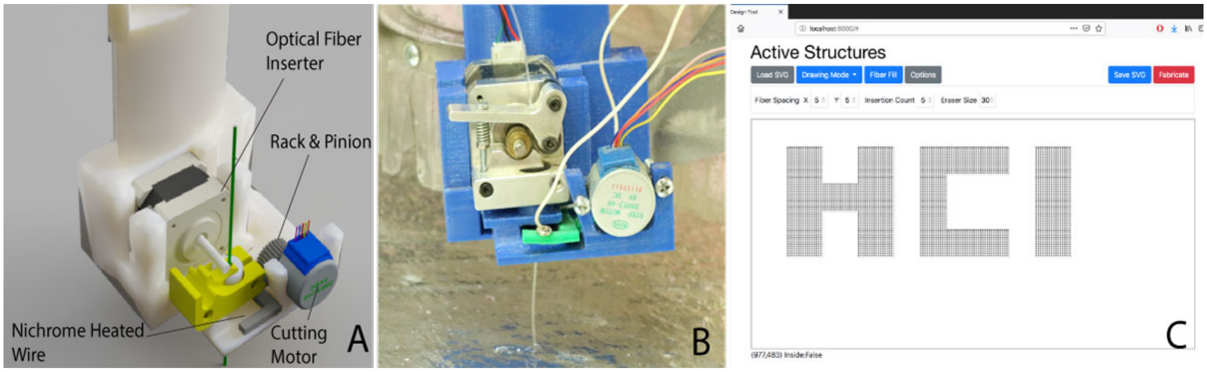


Figure 4.4: Optical Fiber Inserter and Cutter Assembly (A), insertion process (B) and design software (C).

user can start the fabrication process via the "Fabricate" button. Our design tool then communicates the point locations to a Python script that performs the fiber insertion procedure using our hardware mechanism (accurately positioned using a ShopBot CNC Machine).

Display Output

The display output of our embedded optical fibers is controlled by an Adafruit 16x32 RGB LED Matrix[3] that is custom-fitted with a laser-cut mount to hold optical fibers in place. We use an Adafruit Feather M4 Express Microcontroller[4] with an RGB Matrix FeatherWing[5] to power and operate the display.

4.5 Technical Evaluation

In this section, we describe a series of technical evaluations of our proposed system which explore two primary areas: 1) the sensitivity of various cast materials, and 2) the robustness of our sensing system with respect to distance from the sensing unit.

4.5.1 Assessing Material Response

To understand the use of embedded sensing and its performance capabilities in different material types, we explored several material types using the fabrication techniques described above. The intent of this study was to 1) determine the sensitivity of our embedded sensing approach in materials of different composition and hardness, and 2) to understand the frequency content of a given activity in different materials as validation for the frequency-based features described above.

[3] https://www.adafruit.com/product/420
[4] https://www.adafruit.com/product/3857
[5] https://www.adafruit.com/product/3036

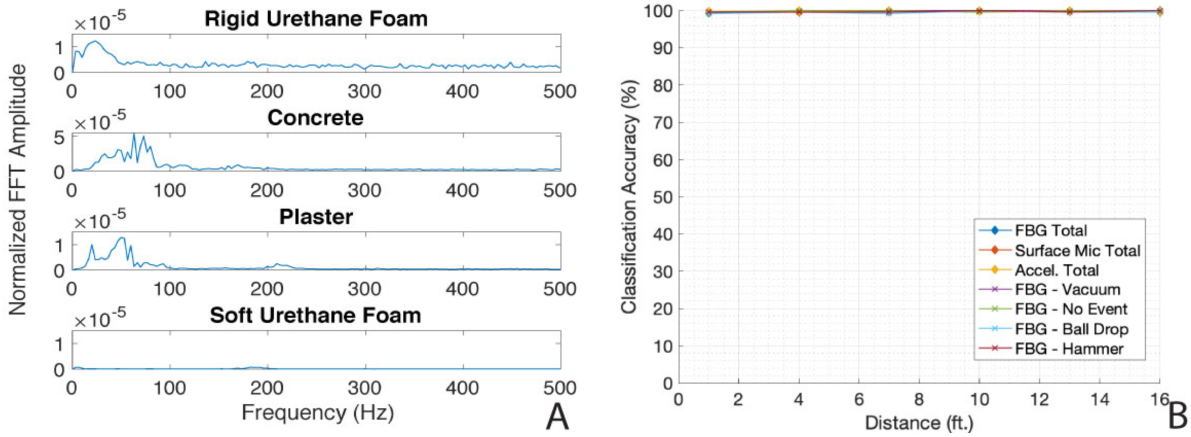


Figure 4.5: (A) Frequency responses for different materials subjected to an impulse hammer excitation. Note the changes in frequency content for each material. (B) Shows Combined classification accuracy of our system with varying distance. We observe that with distances of up to 16 ft, there is not an appreciable decrease in performance of our system.

To control the inputs to the system, we used a PCB Piezotronics 086D20 ICP impact hammer [177]. In this way, we were able to collect both the input forces/excitations to the system (as readings from the impact hammer), as well as the vibration response from our transducers. This allowed us to normalize measured responses by the magnitude of the hammer strike (and thus directly compare each response). We considered four representative materials for this study: concrete, plaster, hard urethane foam, and soft urethane foam. These materials were chosen because they are common building materials, and because of the variety of material hardness levels that they represent. Further, each test specimen was 0.5 x 0.5m with each material; they were placed each on a flat, horizontal surface and struck it at center with the impact hammer.

For each material, we considered the vibration response from our transducers when the cast sample was struck with the hammer several times. Then, we computed the Fourier transform (FFT) of the vibration response for each hammer strike and found the average frequency response across several consecutive hammer strikes. By considering the average response from several hammer strikes, we reduce the effect of noise and outliers on our material assessment. The average FFT response for each material is shown in Figure 4.5 A. In these plots, we consider the entire single-sided frequency response of the material due to the impulse from the hammer strike, which are normalized by the magnitude of the hammer strike force. This normalization allows us to study the distribution of frequency content for each material without the influence of varying input magnitude.

From these studies, we can make a few key conclusions about our embedded sensing approach in different materials. First, we can observe that each material has a unique frequency response from the impact hammer, implying that each is responsive to human interactions and these interactions can be sensed with our system. Second, we observe that the frequency content for each material is different; because of this, our system is sensitive to the material being used and should be calibrated for each application. Third, the frequency content is widely distributed across the range of frequencies, indicating that our approach (which uses the entire frequency spectrum for features) is appropriate for identifying and classifying human interactions with the cast surfaces. Lastly, the "soft foam" raw signal and frequency spectrum response from the impact hammer has a very low signal-to-noise ratio and was difficult to identify from the ambient vibration signal. As a result, we can conclude that while we could identify the hammer strike, soft materials such as the one tested may not be appropriate for less impulsive or lower intensity interactions.

4.5.2 Distance Studies

In addition to the material tests, we explored the sensitivity of our approach and sensing system to estimating activities with varying distance from the sensor. To accomplish this, we deployed our sensing system in a large open area on a wooden gymnasium floor and performed a series of three activities at increasing distances from the sensor (3 ft. increments starting at 1ft.). The FBG sensor along with the enclosure was placed directly on top of the wood floor and fastened with a high-strength fiber tape to create a strong coupling with the floor structure. This coupling ensures that human activity-induced floor vibrations are transmitted to our sensors with as little loss of information as possible. In a long-term deployment, we anticipate that the sensors could be cast directly into the floor structure or a augmented wood panel could be placed in a floor opening and fastened to the adjacent flooring members.

The activities we considered were: 1) a series of ball drops from knee height, 2) running a vacuum on the floor, 3) a series of hammer strikes on the floor, and 4) no event (i.e. no human interaction with the floor). For each activity we collected approximately 300 samples of vibration data for each activity and used this data to train and evaluate our activity recognition classifier. We evaluated each discrete distances (1, 4, 7, 10, 13, 16 feet) independently with a 10-fold cross validation and determined the accuracy at each distance by computing the total number of correctly classified instances divided by the total number of instances. Figure 4.5b shows the results of our study. From these results, we observe that the accuracy of our approach is very high ($> 99\%$) and approximately equal across all distances. Further, this performance is consistent across each activity, with each class having similar performance ($> 99\%$ accuracy) at each distance. This indicates that our system is robust to distance from the sensing unit, and is capable of distinguishing activities through and across a floor at distances as great as 16ft.

Study 1: To compare the performance of the FBG sensors with other common sensing modalities, we collected the same distance study data with a surface microphone (TIMESETL Piezo Contact Microphone) and an accelerometer (ADXL345). To ensure there was no bias due to variation in performing each activity, the data for each sensor was collected in parallel (i.e., all three sensors collected data from the same activity si-

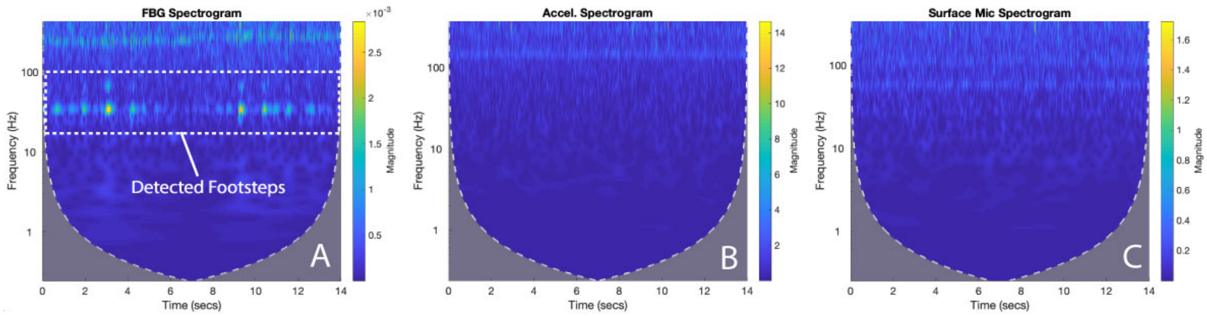


Figure 4.6: Spectrogram showing the footstep detection at a distance of 16 feet for three sensors – FBG (A), accelerometer (B) and surface microphone (C). Note that the FBG can clearly detect many of the footsteps, while there is no visible response from the other two sensors.

multaneously) and used the same activity classification framework. The results for this sensor comparison are shown in Figure 4.5 B). As can be seen in this figure, the FBG sensors achieved the same level of overall performance as the surface microphone and accelerometer ($> 99\%$ total accuracy for each sensing modality for each distance). Based on these results, we can conclude that the FBG sensors have similar sensing capability as the two common vibration sensors considered upto 16ft, and is well-suited to sensing various human activities across many different distances from the sensor itself.

Study 2: The activities considered in the previous study primarily represented only highly impulsive (e.g., ball drop, hammer), or high frequency (vacuum) excitations. To explore the performance for lower amplitude and lower frequency excitation, we considered the ability of each sensor to detect footsteps at a distance of 16ft. The experimenter walked across laterally at 16 feet mark from the sensors. There were 20 steps in total, 10 steps one way, turn around and walk another 10 steps. Our results (shown in Figure 4.6) indicate that FBG are can detect most (>15) of these footsteps while other sensors fail to see any activity. This demonstrates the sensitivity of FBG sensors for subtle human activity such as walking at room-scale (16 feet) and their promising use if integrated into structures.

4.6 Applications

We fabricated two prototypes—an *Active Wall* and an *Active Cement Table*—to demonstrate our fabrication technique. In this section, we describe these room-scale structures and how they enable a series of interactive applications such as an environmentally-responsive contact directory, a passive workshop activity display, and a music player controlled with surface gestures.

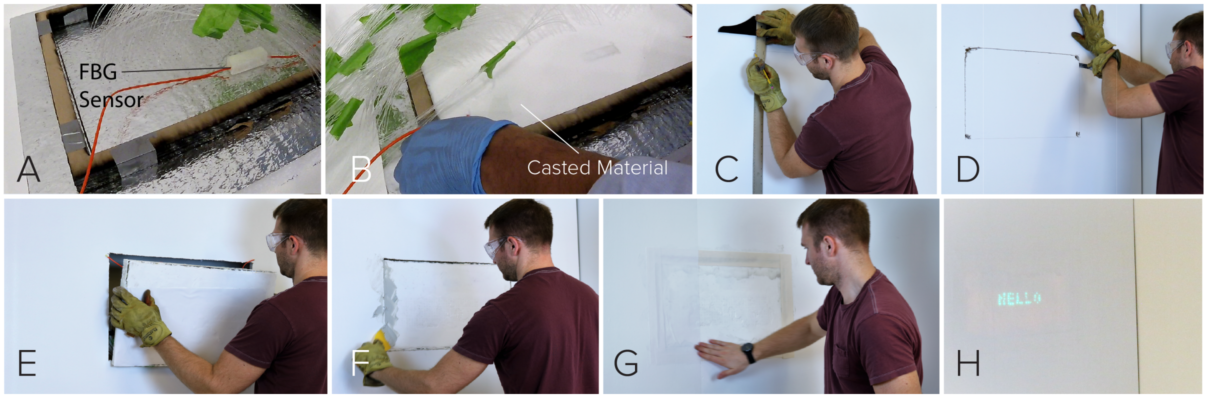


Figure 4.7: Fabrication Process for Active Wall. A FBG sensor is placed into a rectangular mold containing an injected fiber optic display (A). Material is cast into the mold (B). A region of an existing dry wall is removed and replaced with the cast structure (C-G). Finally, the display output of the optical fibers is tested and reveals the message "Hello" on the wall (H).

4.6.1 Active Wall

Our *Active Wall* consists of a cast rigid urethane[6] structure with embedded display and sensor optical fibers. The fabrication process is shown in Figure 4.7. For this example we designed and injected a rectangular matrix of optical display fibers for display. Note that for this prototype of our system, the optical fibers for the display were independent of those used for sensing (FBG sensor), hence can function simultaneously without issues. After placing the optical fiber sensor, we cast the rigid urethane into the mold and let it cure. We measured the structure and removed its dimensions from a pre-existing sheet of dry wall. Lastly, we placed the structure into the wall and finished the surface with joint compound and a uniform contact paper. Figure 4.7H shows the embedded optical fibers activated, displaying the word "Hello".

The Active Wall supports a number of surface-based gestures including swipe, knock, and taps localized to particular areas of the wall (Figure 4.8). The wall is also able to detect events in the environment such as a person walking up to the wall or a power-tool (*e.g.*hand drill) being used nearby. We leverage these interactions with and around the wall to create an interactive contact directory and passive workshop activity display.

Interactive Contact Directory

Our interactive contact directory (Figure 4.9A-D) initially begins in an off-state to conserve energy that is typically consumed by other always-on displays. As a user approaches the wall, the vibrations from her walk trigger a welcome message to appear on the display. The user can then use different surface gestures to interact with the wall.

[6]https://www.alumilite.com/Shared/PDF/Amazing-Casting-Resin-Alumilite-White-TDS.pdf

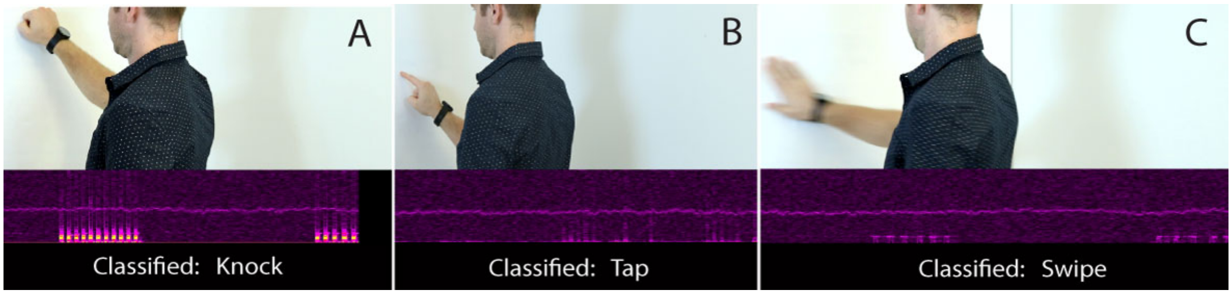


Figure 4.8: A variety of surface gestures such as a knock (A), tap (B) and swipe (C) can be reliably detected in discrete locations as seen in their respective spectrograms.

A swipe gesture dismisses the welcome message and shows the full contact directory. Tapping near the various touch regions (*i.e.*the up / down arrows of the directory) allows the user to scroll through the list. A knock gesture selects a highlighted contact to reveal which direction the user should go to find the selected contact.

Passive Workshop Activity Display

Maker-spaces and lab environments have a variety of tools and equipment that create unique vibration patterns. As another application, our active wall can recognize when these tools are being used and display the magnitude of the vibrations via the wall's embedded optical sensor and display (Figure 4.9 E-G). If another user enters the workshop area while a dangerous tool (*e.g.*a saw) is being operated, the wall triggers a context-aware safety alert (Figure 4.9 H). Finally, detection of these workshop activities can be used to log tool usage over time, supporting automated maintenance reminders, and to let other users know when a particular piece of equipment (*e.g.*laser cutter) is available for use.

Active Wall Activity Recognition Evaluation

We conducted three studies with our smart wall prototype: 1) a gesture study with multiple users to evaluate the ability of our system to distinguish wall interactions, 2) a localization study where multiple users interacted with the wall in different locations to determine the spatial sensitivity of the active wall, and 3) a workshop activity study with multiple users where we explore how well the active wall can sense and distinguish activities occurring in the surrounding environment. All user studies were conducted in accordance with an approved IRB Protocol.

Study 1: Gesture Classification Accuracy

Procedure: In our gesture study, we asked a total of 8 experimental participants to interact with our prototype wall using a series of three gestures: tap, knock, and swipe. The experimental participants age range is approximately 21-33 and there were 7 men and 1 woman. We selected the three gestures above as they are among the most

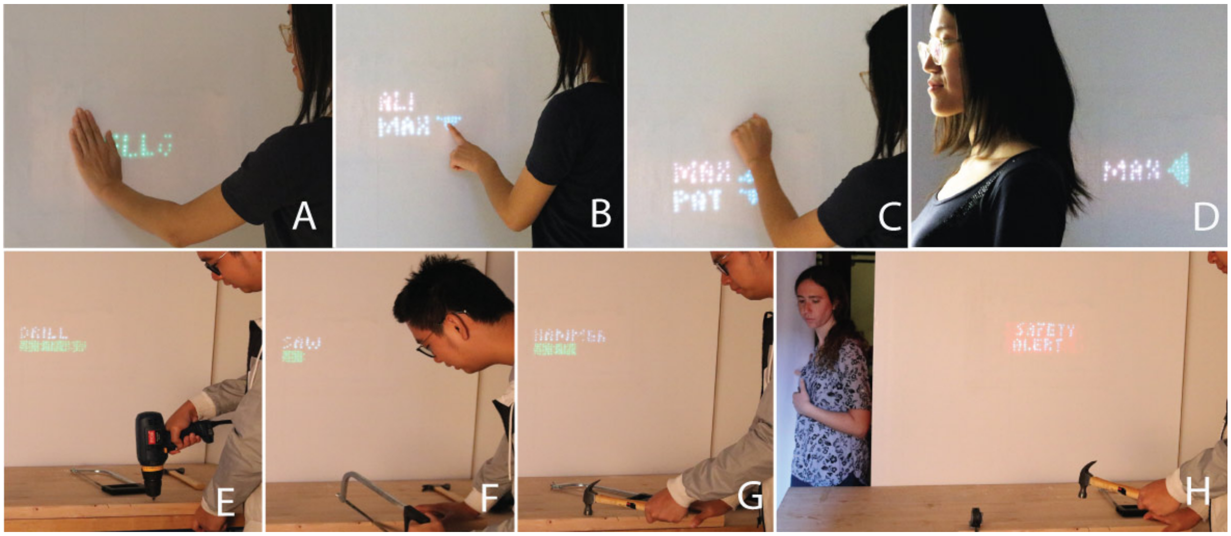


Figure 4.9: Applications of the Active Wall. An interactive contact directory application uses gesture input and visual feedback to guide users to where they need to go (A-D). A passive workshop activity recognition application senses what tools are being used (E-G) and warns users when another person enters the shop area to enhance workshop safety (H).

common and familiar ways to interact with a surface. For each gesture and each user, a total of approximately 300 samples were recorded. We also collected an additional 300 samples of ambient conditions to train a null state (*i.e.*'No Event'). Once completed, the data collected from each user was pooled into one dataset and analyzed using the SVM classifier described above and a 10-fold cross validation to assess the overall performance of our system.

Results: We compute the accuracy of our system for the gesture study as the combined results from the 8 users. The resulting classification accuracy is presented using a confusion matrix in Figure 4.10. In this figure, darker green colored cells represent higher accuracy, while darker red cells represent higher error. Each of the 4 classes (the three gestures and 'no event') achieve high accuracy with few instances of false predictions. The total classification accuracy across all classes is 89.7%. We note that the highest accuracy is from the 'no event' class, which indicates that our approach is able to determine that someone is interacting with the wall with high accuracy. These results indicate that our approach is robust to varying input styles (*i.e.*those from different users), and can accurately determine the type of input; which enables gesture controls for various applications.

Study 2: Gesture Location Resolution

Procedure: In this study, we asked the same 8 users described above to conduct a series of taps at predefined locations on the active wall. The goal of this study is to understand the resolution of the gesture activity recognition and to showcase the abil-

Actual \ Predicted	Knock	Tap	Swipe	No Event
Knock	89.7	6.1	3.6	0.5
Tap	6.0	86.9	6.3	0.7
Swipe	2.4	6.7	86.4	4.6
No Event	0.4	0.8	2.9	95.9

Actual \ Predicted	Loc1	Loc2	Loc3	Loc4	Loc5	Loc6	Loc7	Loc8	No Event
Loc1	83.6	1.4	2.1	2.4	3.6	1.2	2.5	2.0	1.2
Loc2	1.8	81.3	5.9	1.8	1.6	3.0	2.4	2.0	0.3
Loc3	3.9	7.5	67.1	5.6	2.6	3.5	6.2	3.1	0.5
Loc4	5.1	2.5	4.5	69.9	3.1	2.2	4.4	7.3	1.0
Loc5	6.1	1.5	1.9	2.7	72.8	5.3	5.8	3.0	0.9
Loc6	2.9	4.6	2.8	1.5	3.6	72.3	8.2	3.0	1.1
Loc7	4.1	2.6	3.6	3.0	3.7	6.0	71.0	5.5	0.6
Loc8	2.6	0.7	1.6	4.0	1.8	0.6	2.9	84.7	1.1
No Event	0.6	0.0	0.0	0.2	0.2	0.0	0.1	0.7	98.2

Figure 4.10: Active wall classification accuracy for gestures in user studies with 8 participants. The left confusion matrix shows performance of the prototype in identifying common wall gestures (knock, tap, and swipe) across 8 participants. The right confusion matrix shows performance of the active wall in identifying tap locations across 8 participants.

ity of our system to identify the location of the wall interaction. The intuition behind this ability of our system is that interactions in different locations generate unique vibration signatures due to spatial variations in the material itself (e.g., relative position with respect to boundary conditions), and/or amplitude variations due to distance-based signal attenuation. As a result, our system can learn these variations and identify the location of the interaction. The interaction area for this study was a 2ft wide x 1ft tall section of the wall divided into a 6in x 6in grid for a total of 8 tap locations. The "tap locations" represent the center of each grid, and were numbered sequentially along rows, with numbers increasing left-to-right and top-to-bottom. Users were asked to tap in the center of each location in sequence and a total of approximately 300 samples were recorded for each person and for each tap location. The data collected from each user was pooled into one dataset and analyzed using the SVM classifier with a goal of predicting the correct tap location. As before, we used a 10-fold cross validation in our analysis of this dataset.

Results: Figure 4.10 presents results from this study. The total classification accuracy for this study was 77.9%, with the best performance at Locations 1, 2, and 8. Locations 3 and 4 are the worst performers, each with an accuracy less than 70%. Of note is that 'no event' has a 98.2% accuracy, which indicates that our approach can detect a tap gesture in almost all cases (i.e. very few missed interactions). Overall, the results from the gesture location study indicate that there is potential for our system to locate where a user is interacting with the wall, but it has limitations across multiple users. The cause of this observed performance may be due to the variations in how each user taps on the wall. Some users may have a longer duration or different intensity with taps in each location, which may cause confusion in the model at different locations. In our future work we plan to address this limitation by incorporating multiple sensors into the active wall. With multiple sensors, we can combine the classification data with relative amplitude data (interactions closer to a sensor will generate higher amplitude)

Actual \ Predicted	Cutting	Typing	Vacuum	Chair	No Event	Writing	Coffee Mug
Cutting	85.1	3.5	0.0	0.6	0.4	7.3	3.0
Typing	5.8	88.2	0.3	0.6	0.2	3.9	1.1
Vacuum	0.1	0.3	99.1	0.3	0.0	0.0	0.0
Chair	0.8	0.6	0.0	95.8	1.9	0.2	0.6
No Event	0.7	0.1	0.0	2.7	96.0	0.0	0.6
Writing	10.4	5.8	0.0	1.1	0.2	79.7	2.8
Coffee Mug	4.2	2.1	0.2	1.5	2.1	3.5	86.5

Predicted	Walking	Hammer	Drill Press	CNC Vacuum	No Event	Hand Sander	Door Open/Cl	Miter Saw	Laser Cutter
Walking	91.1	1.0	0.6	1.0	0.7	1.7	1.9	1.4	0.5
Hammer	1.3	96.8	0.1	0.8	0.0	0.0	0.4	0.3	0.2
Drill Press	0.4	0.2	97.5	1.5	0.0	0.0	0.1	0.2	0.0
CNC Vacuum	3.6	1.4	1.6	88.3	0.7	0.9	1.0	0.6	2.0
No Event	1.5	0.0	0.0	0.5	84.6	7.3	4.4	0.0	1.8
Hand Sander	1.6	0.1	0.0	0.5	7.2	82.9	5.2	0.1	2.4
Door Open/Close	2.9	0.6	0.0	1.1	5.0	5.5	81.8	0.0	3.0
Miter Saw	3.4	0.7	0.1	0.8	0.0	0.3	0.1	94.6	0.1
Laser Cutter	0.5	0.2	0.0	2.2	1.9	4.7	2.6	0.1	87.9

Figure 4.11: Confusion matrices for various events on two interactive structures. (A) shows performance of embedded coffee table unit in identifying various activities. (B) shows performance of the active wall in identifying various shop activities.

and/or time difference of arrival information (which has been shown in prior work to be effective for localization with human-induced vibration signals [150, 171]) to improve the localization capabilities of our system.

Study 3: Workshop Activity Identification

Procedure: In the final study for our active wall prototype, we explored the performance of our system with respect to activities that occur in the surrounding environment. Therefore, we conducted a series of activities in the space surrounding our prototype wall to simulate a "workshop". The activities studied include (approx. distance from sensor in parentheses): using a table saw (15ft.), walking around the workshop (~5ft.), using a hammer on a table (12ft.), running a miter saw (7ft.), opening/closing a shop door (32ft.), operating a drill press (8ft.), operating a laser cutter (32ft.), using a hand sander (12ft.), running the vacuum system for our CNC router (8ft.), and 'no event'. These activities were chosen as being representative of common tools/activities that would take place in a normal workshop environment. The distances described in the workshop study reflect the actual location for each tool/activity from the location of the sensor/wall. These locations, therefore, reflect a real-world workshop layout and not one that was tailored for best performance of our system. Our experimental dataset for this study consisted of 8 total users with approximately 300 samples per person and per activity, for a total of approximately 21,000 samples. We computed the total classification accuracy for each event across all users with a 10-fold cross validation.

Results: Figure 4.11 b) presents a confusion matrix for this study. We observe that the best performance is in identifying operation of the drill press,hammer, and miter saw (97.5%, 96.8%, and 94.6% accuracy, respectively). We note that these particular activities are either 1) very close to the wall, and/or 2) have very high intensity vibrations. As a result, the recorded signals are very distinctive and our system is able to identify these activities with very high accuracy. Further, the worst performing activity is 'Door Open/Close', which primarily gets confused with the the hand sander and 'no event'

Figure 4.12: Applications of the active table including activity recognition of interactions on and around the table (A-E) and a gesture based music player that uses tap, swipe, and knock. as input control for a music player.

activities. In this case, the door open/close is very far from the sensor; as a result, the recorded vibration signal is of very low amplitude and the vibration frequency content is similar, making it difficult to distinguish it from the ambient vibration condition (no event). Overall, the average classification accuracy across all activities is 89.4%, which indicates that our system is able to accurately identify indirect activities in the surrounding environment.

4.6.2 Active Cement Table

We fabricated an Active Cement Table with embedded optical fibers and a sensor using polymer-modified, rapidly curing structural concrete[7] as seen in Figure 4.3. We created a mold using the CNC mill, then used our fabrication process to insert a rectangular matrix of optical fibers. After manually placing an enclosed sensor and wooden support legs for the table, we poured and smoothed the concrete and allowed it to cure.

Similar to the Active Wall, our table can detect knocking, swiping and tapping on its surface. Additionally, the table can detect other surface-based interactions common to its typical use in home or coffee shop. For example, the table can sense when a user is writing a note, typing on their laptop, or placing their coffee mug down. Activities in the environment such as a vacuum running or a person sweeping the floor are also detectable. Figure 4.12 shows an example of some activities measured on/around the active table and their associated spectral responses (which are used for classification).

[7]https://www.amazon.com/dp/B078753CQW

Surface Gesture Music Player

Our Active Cement Table functions as a gesture-controlled music player. When the user knocks on the surface of the table, music begins to play. A swipe gesture then advances to the next track of a playlist. Finally, knocking again turns the music off. An example of this application is shown in Figure 4.12 F-G.

Around Table Activity Awareness

Sensing activities around the table enable a variety of context-aware applications. When a user begins to vacuum the floor, their music can be automatically paused for the duration of vacuuming. The music can then be resumed once the vacuuming is completed.

4.6.3 Active Cement Table Evaluation

To evaluate the performance of our active cement table prototype, we conducted an activity recognition study which incorporates activities occurring both on and around the active table.

Procedure: For this study, we had 8 users conduct a series of activities on the active table prototype, and then in the surrounding environment. This combination of activities enables us to evaluate the performance of our system with regards to horizontal surfaces, and with room-scale activity recognition. The activities on the active table include: typing on a keyboard, placing a mug on the table, writing on a notepad on the table, and using a knife to chop food on the table (e.g., an apple). Then, for activities surrounding the table, we considered the following: vacuuming the floor, and sliding a chair into/out of the table area. Similar to the active wall evaluation, we collected approximately 300 samples of each activity across 8 different users (approx. 16,000 total data samples) and analyzed our system's classification accuracy using a 10-fold cross validation.

Results: Using our approach, we were able to classify 7 activities (6 listed above and 'no event') with a total classification accuracy of 90.1% for our multi-user recognizer. The full results are presented in Figure 4.11 A. From these results, we can observe that the best performing activity is the vacuum (99.1%), while the worst is writing (79.7%). We note that the writing activity is typically of low intensity, which can lead to confusion with other table activities (i.e., cutting and typing). With its accurate performance across activities both on vertical (active wall) and horizontal (active table) surfaces, we demonstrate that our system is capable of sensing room-scale activities with multiple users.

4.7 Discussion, Limitations, & Future Work

4.7.1 Sensing of Simultaneous Activities and Interactions

We have leveraged machine learning to sense different interactions on and around our interactive structures. In our technical evaluation, we focused on sensing events independently. However, as future work it may be advantageous to support classification of simultaneous events. For this purpose, we are interested in exploring a multi-level SVM classification approach similar to [128, 192] and using a network of sensors as in [124] to detect simultaneous events with our system.

4.7.2 Building-Scale Sensing Infrastructure

Current work demonstrates the feasibility of our sensing approach being integrated into existing infrastructure and/ while building new structures. In future, we aim to scale our approach across different sections of a full-scale building such as walls, floors, etc. by combining multiple FBG spread across different rooms and floors, all while connected through single mode optical fibers [8] which are interrogated from a single point. Compared to traditional approaches (i.e., wireless sensors/wired sensors), this approach could offer battery and electronics-free sensing at building scale.

Additionally, a practical way to scale FBG sensing into buildings or cities may be to combine them with already existing optical fiber networks for internet/intranet communications. For instance, google fiber [9] offers services by extensively reworking public and private infrastructure with optical fiber networks. By utilizing such intricate optical network may be one way forward to scale sensing approach to building/city scale.

4.7.3 Material Selection for Interactive Structures

The cast material's curing process should be considered when incorporating FBG sensors into structures. In general, the FBG sensor functioned correctly in the various materials we had cast around it. However, we found poured concrete requires one additional consideration– concrete cures through an exothermic reaction. In our initial experiments, we found the vibration transducer enclosure (3D printed with PLA) would deform slightly under the heat, affecting the signal response. To address this during fabrication, we coated the enclosure in a high-temperature epoxy[10]. This issue could also be resolved by fabricating the enclosure with a high-temperature resistant plastic or ceramic material.

[8] https://www.cablewholesale.com/specs/10f2-006nh.php
[9] https://support.google.com/fiber/answer/6124985?hl=en
[10] https://www.digikey.com/products/en/tapes-adhesives-materials/glue-adhesives-applicators/909

4.8 Summary

Our work demonstrates a fabrication approach to embedding input and output into the construction of room-scale objects using optical fibers and Fiber Bragg Grating optical sensors. We show through technical evaluations the robustness of FBG sensors with respect to embedded material type and activity distance and compare the performance of our system with common sensing modalities. To showcase the ability of our system to monitor human activity, we evaluated its accuracy across two real-world prototypes with 8 different users and observed a high classification accuracy as much as 89.4% across as many as 9 different activities. Our technique enables a rich application space for interactions occurring on and around these structures. Mark Weiser once stated that the most profound technologies disappear by weaving themselves into the fabric of everyday life. We view our work as a literal building block towards this vision of Ubiquitous Computing by enabling HCI researchers and practitioners to explore interaction with smart structures in big way.

Chapter 5

Fiberwire

5.1 Introduction

In the previous chapter, we discussed approaches to create custom room-scale interactive structures by embedding optical elements for sensing and displays. While this approach enables novel capabilities, it is mainly limited to cast materials and form factors enabled by the materials used. With the rapid growth of new digital manufacturing technologies — most notably additive manufacturing or 3D printing — offers many new opportunities in terms of materials, processes and customization. These techniques can enable users to quickly realize their digital designs in ways that were not previously widely available. For example, 3D printing enables the creation of some geometric forms which are not manufacturable in other ways and can support the manufacture of highly customized products on demand.

However, there are a number of limitations in current techniques which need to be overcome to reach this goal. Some of these limitations regard the materials available for 3D printing as well as the ways in which we can achieve multiple functions within one print with those materials. For example, most current print materials (e.g., various polymers) are not structurally strong and in the context of our vision, we are mainly focused on structural materials used in built environments. Fortunately, recent advances in new printing materials and processes are starting to provide new alternatives which can overcome these limitations. In this chapter we explore the possibilities opened up by one of these new technologies: the ability to 3D print continuous fiber carbon composites. While the strictly in-layer deposition of carbon fiber supported by current technology still produces parts with anisotropic strength properties (i.e., they are much stronger within a print layer than across print layers) they are still very strong, and vastly stronger than typical plastic-based 3D printed objects. For example, typical plastics used for 3D printing such as PLA can have tensile strength up to 50 MPa (in bulk form) [9], compared to 700MPa in carbon fiber composites [7]. Further 3D printed carbon fiber composites offer a range of process advantages such as the ability embed electronics,

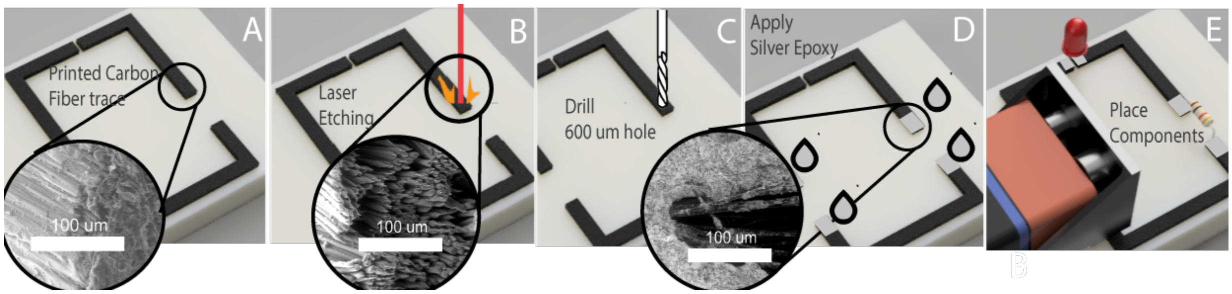


Figure 5.1: FiberWire Fabrication workflow: (a) 3D printing of carbon-fiber trace circuit, inset shows SEM image of the carbon-fibers bonded with epoxy in the resin matrix (b) Laser etching of epoxy to expose raw carbon fibers, inset shows results of laser etching (c) Drilling micro holes for interfacing with electronic component pins (d) Deposition of silver epoxy on exposed carbon fiber, inset shows carbon fibers are coated with conductive silver and (e) Placement of the components

and support for multi-material printing, that are not found in other 3D printable strong materials. In the work presented here we seek to extend these capabilities in several important ways to move them towards the eventual goal of wholly printable interactive devices that can remain interactive even when handling thousands of pounds of impact forces.

We first introduce a fabrication process that enables us to use the carbon fibers as conductors to form interior electrical circuits within mechanically strong printed composite parts. This allows us to more easily embed electronics by making the wiring an integral part of the print rather than something added later. Next, we show that sensing techniques which have been highly successful in conjunction with other materials (e.g., sensors based on changes in capacitance [82]), can be readily adapted to this setting. We showcase a range of sensors that can be printed in-situ along with circuitry in carbon fiber composites in a single print. We also demonstrate the performance characteristics of these sensors on new materials such as carbon-fiber composites. Finally, we showcase three full example objects which embody both mechanical strength and are interactive – a bicycle handle bar with interactive controls, a swing and impact sensing golf club and an interactive game controller.

5.2 Fiberwire Fabrication Pipeline

In this section, we introduce the steps involved in fabricating structurally strong, interactive carbon composite electronic devices. The fabrication process of FiberWire consists of 5 major steps: (i) 3D printing of carbon-fiber composite structure with traces, (ii) selective laser etching of epoxy to expose raw carbon fibers on printed traces (iii) drilling micro holes for interfacing with electronic component pins (iv) deposition of silver epoxy on exposed carbon fiber and (v) placing the components. Next, we consider the steps in detail.

5.2.1 Printing Traces

The fabrication process of FiberWire utilizes the Markforged (MarkTwo) multi-material 3D printer [8] that can programmatically lay out long strand carbon fiber (pre-impregnated with a heat sensitive epoxy resin) as well as other dielectric material such as nylon. The fabrication process begins with a geometric model of an object with embedded circuit traces which is loaded into the unmodified printer software [1]. In addition to specifying base geometry, the software allows us to fill the geometries with both carbon fiber composite and nylon, with an ability to selectively specify layers with different orientations and directions. After experimentation with available settings, we determined that good results could be obtained in single layer traces with a width of at least 3mm.

The printed electrical trace consists of continuous fibers laid along the path of the trace. A close look at the trace using a scanning electron microscope (SEM) (Fig 2A inset) reveals that, as expected, the carbon fibers are held together in an epoxy resin matrix. However, the epoxy that holds the fibers also reduce the conductivity into and between the fibers.

5.2.2 Laser Etching

To remove the epoxy and establish better electrical contact, we programmatically pause during the printing of each circuit layer and use laser etching to remove the epoxy (Figure 5.1 B) from positions of external contacts and vias. As can be seen from the SEM imagery in Fig 2B inset, the raw fibers are exposed as result of this etching process. During this etching process the epoxy is burned away and the raw carbon fibers underneath are carbonized.

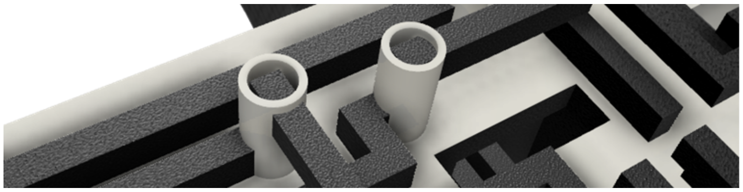
In the work reported here, we used a stand-alone commodity CO2 laser cutter (Universal PLS6.150D) in raster mode (12% speed and 100% power) for laser etching. Markforged printer's print bed has magnetic alignment pins (10um accuracy) that allows us to stop printing at a specified layer, take the partially printed object out with the print bed and switch to the laser cutter. However, it should be straight forward to integrate a high-power laser diode directly into a similar printer for this purpose in the future.

5.2.3 Holes, Silver Epoxy & Components

After laser etching, we mechanically drill holes of 0.6mm diameter on the trace (Figure 5.1 C), this enables us to connect the off-the shelf electronic components. While the removing the epoxy improves the conductivity, there is further contact resistance between pins and raw fiber traces. Hence, we coat silver epoxy (2-part MG chemicals 8331) on areas where electrical components need to be inserted (Figure 5.1 D).

Finally, we place the electronic components by inserting them into the holes, bonding them in place with silver epoxy (Figure 5.1 E). The silver epoxy helps form better

[1] www.eiger.io



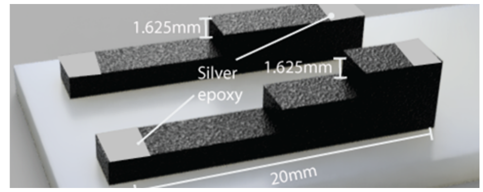


Figure 5.2: a) Shows cylindrical via printed between traces layers b) Resistance characterization test between layers

electrical connections with the components by reducing the contact resistance and also structurally supports our components, ensuring they are mechanically bonded well with the traces.

5.2.4 Printing Vias:

We printed vias as cylindrical holes in nylon with traces from each layer leading into these cylinders (Figure 5.2). To further establish better contact between carbon fiber layers above and below, we laser etch the traces within the cylinders. Finally, we fill the via cylinders with silver epoxy to keep the traces in place and further improve conductivity. Our via designs worked well with a measured resistance less than 2 Ω.

5.3 Basic Electrical Perfomance

5.3.1 Conductivity in Single Layer Traces

To characterize the performance of our fabrication approach, we tested 6 samples of varying lengths 5, 10, 15, 20, 25 and 30cm (maximum length of the printer) for three conditions: a) resistance with original epoxy b) resistance after laser etching b) resistance after laser etching and silver epoxy deposition. We used a 2-point resistance measurement for estimating resistances. We found that in all sample lengths better conductivity is achieved when traces are both treated with laser for epoxy removal and deposited with silver epoxy. As explained in the fabrication pipeline, the observed effect is due to exposition of conductive raw carbon-fibers and the reduction of contact resistance by the silver. We summarize the test results in (Table 5.1).

Further, the mean resistivity for our cross sectional area (4.995mm^2) was found to be 3.669×10^{-4} Ωm (*SD* = 9.1×10^{-5}). Also, from the (Table 5.1) a linear regression on the silver epoxy condition found the overall fit to be r^2=0.929. The constant coeffcient (contact resistance x 2) was measured to be 3.41 Ω

The results indicate that, it is possible to fabricate highly conductive carbon-fiber traces at the maximum length of the printer with resistances which compare much better than current conductive material approaches employed with polymers.

5.3.2 Conductivity Between Multiple Layers

Conductivity between the layers for fabricating multi-layer circuits was also tested. We printed traces with steps of varying thickness (1 step = 1.625mm). We ran resistivity measurements on samples with 2 steps and 3 steps (**??**). We observed a mean resistance of 28.2 Ω (N =5, SD = 4.09) for 2 step and 75.32 Ω (N =5, SD = 3.03) for 3-step (after laser etching and silver deposition in the marked areas). The results indicate that the increase in resistance across Z-direction is due the epoxy in between layers.

5.4 Sensor Designs

Taking advantage of the FiberWire fabrication process, we provide a range of custom sensor designs that can be fabricated with carbon-fiber composites and be embedded with electrical circuits. Each of these designs makes use of a capacitive sensing [82], thus demonstrating that our materials and processes can easily support integration of this widely used, successful and well supported sensing approach. In this section we illustrate our sensor designs and provide performance characterization of sensors within objects created by our process.

5.4.1 Sliders

We designed sliders with carbon fibers acting as capacitor plates. The sliding element (Figure 5.3 A) moves across the rails of the slider to support this motion. One of the triangles underneath the sliding element is connected to ground and the other is connected to one of the pins of the sensing circuit. As the sliding element moves (Figure 5.3 B) the active area of the capacitor changes and as a result the capacitance of the system changes. We capture this change by using an Arduino and an MPR121 capacitive sensing chip (which has 12 sensing pins sampling at a framerate of 29 Hz).

The MPR121 reports a digital value proportional to the capacitance at the input. We observed a change of 20 raw sensing units (on a scale of 0 to 1023) from one end of the slider to the other. (**??**) shows a slightly non-linear relation between the distance

Table 5.1: Resistance characterization tests

Lengths (cm)	Printed Carbon Fiber (Ω)	Epoxy Removal (Ω)	With Silver (Ω)
5	90	33.1	5.3
10	120.4	35.4	7.9
15	130	40.6	10.9
20	118	43.6	12.4
25	149.4	44.3	17.1
30	175	48.5	15.8

Figure 5.3: a) Shows the sliders fabricated with FiberWire. We used a triangular design varying the capacitor plate area b) Shows the assembly of the slider. Note that prints of all printed examples have been done using a white nylon base with black carbon fibers to make material placement apparent. c) Shows the characterization of capacitance vs displacement behavior of our slider across the device

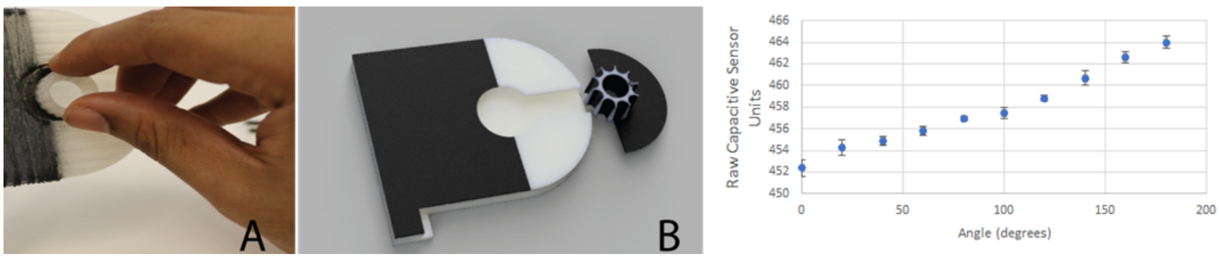


Figure 5.4: a) Shows the rotary encoders fabricated with FiberWire. The casing includes partially filled carbon fiber in semi-circle and the knob fully filled with carbon fiber b) Shows the assembly of the encoder c) Shows the characterization of capacitance vs angle of our rotary encoder design

of the slider to the thick end of the triangle and capacitance. We repeated the characterization test 12 times to estimate the accuracy of the measurements. Although the change in values over the entire range is relatively small (20 units), the accuracy of each measurement is within 1 unit.

5.4.2 Rotary Encoders

We also developed a rotary encoder which senses the capacitance change as a conductive plate moves between ground and sensing plates located in the casing. We fabricated the casing to be half filled with carbon fiber and the rotating plate to be completely filled (Figure 5.4), hence the rotary encoder can sense angles between 0-180 degrees. When the knob is rotated and the plate moves between the casing sensing and ground plate, it results in a change in capacitance. We characterize the behavior of the knob sensor in the same way as the slider. The (nearly) linear relation between the angle of the knob and the capacitance is given in (**??**). The characterization test was repeated 8 times and the accuracy was found to be within 1 unit across those trial

5.4.3 Capacitive Touch Buttons

Because of the nature of 3D printing, we can fabricate custom touch sensors in any geometry we would like. Once designed, a range of custom shapes can be filled with conductive fibers during the print. The sensors could additionally be covered or filled with nylon layers. We use this method to print touch sensitive buttons in different shapes of pause, play and stop buttons in our example applications

5.4.4 Tactile Buttons

We fabricated tactile buttons with a plunger that is loaded with a printed spring and moves in between two capacitor plates (**??**). We measured the change in capacitance in the same way as the slider and the rotary encoder. We set a threshold for the capacitance change to detect whether the button is pressed or released and across 200 trials for each button and they worked with 100% accuracy.

5.5 Example Applications

In this section we detail three example applications that are both structurally strong and contain integral interactive controls. All our examples utilize the FiberWire fabrication workflow and sensor designs introduced earlier.

5.5.1 A bike handlebar with embedded touch sensors, and lights

We envision using FiberWire techniques in an automated way to create many mechanically strong carbon fiber composite objects such as bicycles, calipers, drones, sporting gear etc. with printed multi-layer electronic circuits and interactive controls embedded inside of them. We show a proof-of-concept: a carbon fiber bike handlebar (Fig 11) printed with interactive controls and embedded electronics using FiberWire fabrication techniques.

Overview of Traces:

We 3D printed all the layers of the bike handle bar including the three layers of circuitry embedded inside (Figure 5.5 A and D) in a single print. The circuits in the bottom most layer (Figure 5.5 D) consist of 3 pairs of traces, with each pair of traces connecting to ground and a digital pin from a microcontroller. They are routed to turn signal lights at the left and right side of the handle bar and another pair of traces route to the headlight for the bike handle bar. The middle layer (Figure 5.5 D) of carbon fiber composite circuits are connected to the top layer and bottom layer through vias (Figure 5.2). All our electronic components are housed in the top most layer of the circuit.

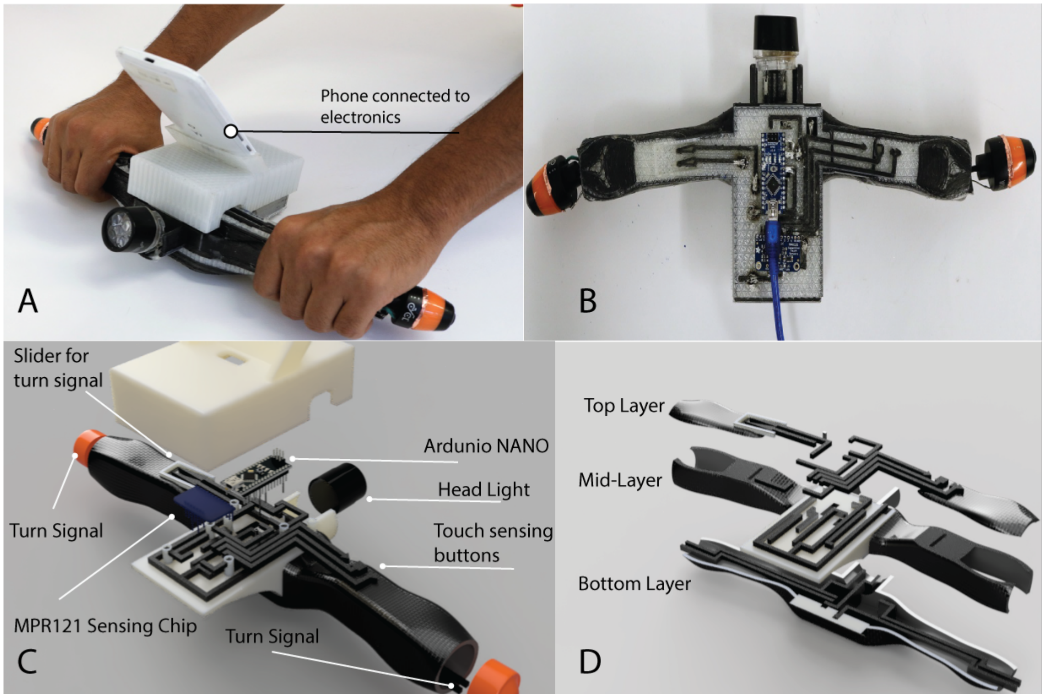


Figure 5.5: A user holding a full body bike handle bar with embedded carbon fiber circuitry and touch controls. b) Shows the top view of the circuit with components placed on top of the circuit. c) Shows an exploded view of the electronic components which include: headlight, turn lights, and printed touch controls, printed slider, Arduino Nano microcontroller, MPR121 touch sensing board and mobile phone casing. d) Shows three layers that go into the handle bar circuitry printed over layer by layer and connected by vias.

Electronic connections:

All our electrical connections are made possible through the FiberWire fabrication workflow described earlier. In this section, we detail how the traces are connected with the electronic components.

In our bike handle bar example, we placed an Arduino Nano microcontroller (Atmega 328p) (Figure 5.5C) and interfaced it with a MPR121 capacitive touch sensing chip on a separate board. The sensing chip interfaces (I2C & Power) with the microcontroller through our carbon fiber traces printed using FiberWire fabrication process. Further, we printed traces from the MPR121 board to run along the top surface near the right side of handle bar grip towards three touch sensing buttons. The touch buttons consist of play, pause and stop which control the music player in a connected phone using the microcontroller over a serial connection.

On the left side of the handlebar grip (Figure 5.5 C), there is a capacitive slider that is connected to the MPR121 board which controls the turn signals in the bottom layers of the handle bar.

Finally, to power all the electronic circuitry we use a commodity mobile phone and connect the microcontroller to the phone through an OTG-USB cable. The mobile phone sits in a printed casing shown in Figure 5.5 A.

Evaluation of Strength:

We tested the mechanical strength of our bike handlebar using an Instron 5969 universal material testing machine. We clamped the center of the handlebar to the testing machine and applied an increasing load to one of the handles until the deflection of the handle prevented the tester from applying more load. (The handle did not break during testing, or in fact show any visible signs of damage.) Referring to **??**, the maximum load at this point is measured as 1110±11 N. For comparison, the maximum load applied to a handle bar in off-road trails has been reported as 200 N [59].

5.5.2 An interactive Golf club with embedded IMU and RF Microcontroller

We fabricated a golf club that trains people to make good golf strokes with interactive feedback (Figure 5.6A). The golf club consists of a multi-layer carbon fiber circuit embedded with an IMU, a Bluetooth capable Arduino module (Simblee) and a coin cell battery unit (Figure 5.6(B-C)). The IMU unit is an MPU-9250 9-axis MEMS sensor, that returns acceleration values upon impact and stroke. The IMU is interfaced with the Bluetooth module which sends the data to a Phone or other Bluetooth connected device.

Evaluation of Strength:

We test the impact strength of our golf club by dropping a steel ball with a mass of 4 kg from heights starting from 10 cm and increasing with 10 cm steps until the club breaks (Figure 5.6D). By doing so we increase the impact energy delivered to the golf club by simply increasing the initial potential energy (which changes linearly with the height and the mass of the ball). We chose to test the golf club with impact instead of simply loading as we did for bike handlebar since the golf club operates under impact conditions (hitting the golf ball).

To compare the impact strength of 3D printed carbon-fiber composite, we repeated the same test with a 3D printed PLA & ABS golf club. We chose the density of the filling of PLA & ABS to the maximum during 3d printing. The masses of the carbon fiber golf club and PLA golf club are measured as 128 gr and 160 gr, respectively. The carbon fiber golf club failed at a drop height of 60 cm (initial potential energy of 23.54 J) while PLA & ABS golf club failed at a drop height of 30 cm (initial potential energy of 11.77 J). We repeated the experiment two times (with newly printed golf clubs) and obtained the same result. Our experiment results show that the 3D printed carbon fiber composite has double the impact strength of the 3D printed PLA/ABS despite being lighter in weight.

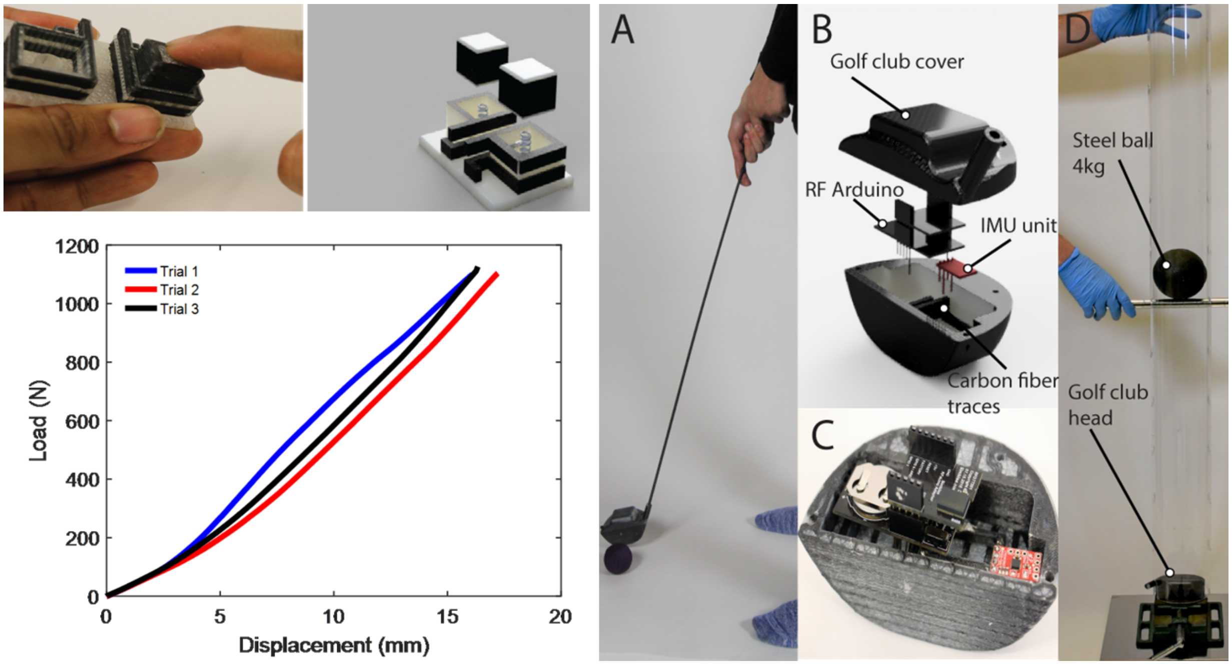


Figure 5.6: a) Shows the golf club with a user b) Shows the exploded view of golf club with RFduino and accelerometer c) Shows the top view of the fabricated sample d) Shows the drop ball impact test of the golf club head. e) Bike Handle Bar Strength Testing f) Shows the fabricated tactile buttons with two fiber traces embedded with a nylon layer in the middle. g) Shows the caps that go with the buttons which are also fabricated with carbon fiber

5.5.3 An LED "Mario" game with tactile switches

As an additional application we fabricated an interactive game controller (Figure 5.7A) with multi-layer carbon fiber circuitry. The game controller consists of an LED matrix, an Arduino Nano to drive the LEDS (with firmware implementing a 64-pixel approximation of a "Mario" game), resistors and an MPR121 board to offer capacitance sensing. All components are connected through multi-layer carbon fiber circuitry as seen in Figure 5.7B. The LED matrix display shows "Mario" as a red led dot and the level maps are displayed using the 64 LEDs as a small display. As the user pushes the tactile button on the right side of the game controller, the Mario dot moves to the right. The left side tactile button is used for controlling the jumps of character.

5.6 Discussion and Limitations

There are a few limitations in our approach to embedding electronic function into carbon-fiber composites. First, our current workflow to embedding circuits on 3D objects is done manually using solid modeling tools (Solidworks, Fusion, etc). We design trace geometries and then create SVG layers for laser etching on specific sites of the traces.

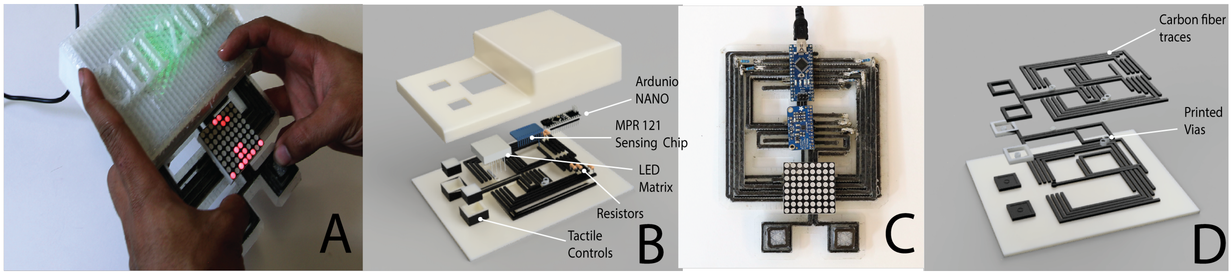


Figure 5.7: a) A user holding an interactive game controller with two tactile buttons that help play a "Super Mario" game with the LED matrix. b) Shows the exploded view of all the components that are housed inside the game controller i.e., LED matrix, Resistors, Arduino Nano, MPR 121 capacitive sensing board. c) Shows the components placed in the circuit from top view. d) Shows multiple layers of carbon fiber circuits that connect the electrical components, and capacitive sensing tactile buttons.

The process could be streamlined in future by having a design tool to simultaneously accept existing trace files – gerber files – and 3D geometeries to automatically identify contours of the object to merge with trace routes. Similarly, in a semi-automated manner programmatic pauses could be inserted by the tool to support switching between laser cutter and printer.

Second, printing time for objects is similar to other FDM processes. The golf club head prints in 16 hours. In between the laser etching process takes about 10 secs for each trace and an entire layer 2-3 minutes (if it contains several electrical connections). This could be further improved by integration of multiple processes (laser and print) into a single machine.

Finally, access to continuous fiber fabrication machine may be limited due to early adopter pricing, however in future costs may further go down as new competitive printers [4] are introduced. Furthermore, FiberWire fabrication approach may also be used in a DIY setting by using other manufacturing methods such as hand-layup [145] for fabricating composites. Users can manually stack layers of woven carbon-fiber (conductive) with other fibers such as glass fibers (non-conductive) and selectively apply epoxy to form circuitry and composite devices.

5.7 Summary add Future work

With FiberWire, we have introduced new capabilities to engineer carbon fiber-based circuitry inside of mechanically strong parts. We described a repertoire of methods that exploit the electrical characteristics of carbon fiber composites – specifically, demonstrating how to fabricate carbon fiber composite objects with embedded multi-layer circuitry which can directly support the kind of capacitive sensing that has been successful in other fabrication processes. We envision our methods of laser etching and silver deposition could be incorporated directly into a future carbon fiber printer since the current printer already supports a precision motion platform with two types of deposition heads. Specifically, similar printer hardware could also include a high-power laser diode (for etching) and a paste deposition pump (for silver paste). By utilizing our techniques, we hope engineers and designers can fabricate structurally sound and functional interactive objects in the future.

Chapter 6

Deployable Structures

6.1 Introduction

In the previous chapters, we explored enabling room-scale interactivity into built envrionment formfactors with two approaches (1) Digital Casting and (2) Additive manufacturing, these approaches enable bespoke interactivtive devices with built envrionement materials like cement, carbon composite, plaster, etc. However, the functionality enabled by such material techniques still misses actuation, which has demonstrated deep benefits in HCI [191]. In this chapter, we look to explore interaction with a class of deployable and actuatable interactive objects that can be custom fabricated at built environment scale: pneumatically inflated deployable interactive structures. Our addition of interactivity allows these structures to move from supporting environments constructed with passive forms, to interactive forms which can respond to user input, and thus create responsive environments.

6.2 Motivation and Contribution

Most structures around us are built and then, often with considerable effort, retrofitted with custom sensors, IoT devices, and actuation (e.g., automated doors/windows with proximity sensors). Our overarching goal is to develop techniques for fabrication of sensors and actuators as an integral part of the structure manufacturing processes itself rather than added later.

We do this in the context of deployable structures [72] which offer further responsiveness and flexibility in an environment since they can be deployed and removed on demand. In general, deployable structures include those which have a compact (undeployed) state that can be expanded into a larger and/or more functional configuration. Many scenarios exist with interactive deployable structures where inferring user context and providing support for interaction can improve user experience. A non-exhaustive list of example scenarios includes a storage box structure that opens and retracts when a

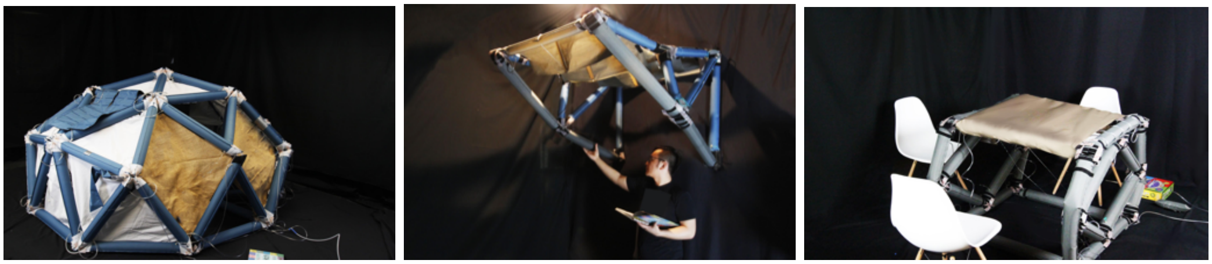


Figure 6.1: (a) A geodesic dome that deploys itself upon inflation and has embedded actuation and acoustic sensing to open its doors and raise its windows; (b) a canopy with a controllable venetian blind via capacitive sensing; (c) a portable table inflated on-demand via a pressure sensitive control. All of our structures have embedded actuation and sensing that support a range of interactions (e.g., a user performs a knock gesture on the dome's door and the door swings open).

correct key-code is pressed; blinds which sense weather conditions and automatically open and close; a self-deploying table which expands when it senses multiple users; an interactive chair with controls to adjust backrest, etc.

In this work, we have chosen to consider inflatable structures of this type for a number of reasons. Inflatable structures often offer a large expansion ratio from their compact to deployed states. Many useful objects can be custom fabricated using comparatively easy to work with materials, and manageably small fabrication machines; and the deployment of these structures is fully reversible so that they can be deployed and redeployed on demand. To explore the interactive possibilities around this space of objects, we introduce several techniques for basic input sensing, as well as actuation mechanisms and a holistic construction method for collectively (sensors, actuators and structures) putting together room-scale interactive deployable structures, i.e., structures which can respond to human input and implement interactions. We also consider several example objects which can be built using these techniques (Figure 6.1).

To this end, we contribute a toolbox of basic sensing and actuation methods, that designers can use with our uniform and relatively simple structural manufacturing process. Main requirements for input sensing were employing materials already in use and supplying a reasonably rich set of basic primitive, reusable, interaction techniques. Hence we selected a wide variety of sensing methods – capacitive sensing [82], swept frequency ultrasonic sensing [125] and pressure sensing [87] – that can be adapted to work with our structural members (trusses).

Similarly, we contribute three classes of soft actuators for manipulation of structures: linear (increase/decrease in length) used in pull/push of articulated joints, bending and twisting. Our actuators are inspired by a growing body of soft robotic literature such as pouch motors [160], gait robots [208] and continuum arm robots [196] where the actuators have been thoroughly modeled and tested with materials such as PDMS (commonly referred to as silicon rubber). Note that, we extend this literature by implementing them

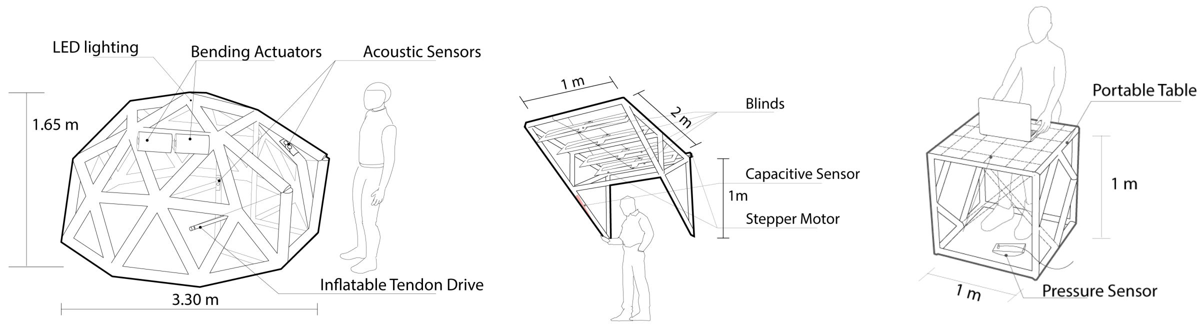


Figure 6.2: (a) An overview of an interactive geodesic dome with various actuators and sensors embedded as a part of the structure; showing the placement of contact microphones that are used to detect user gestures via swept frequency ultrasonic acoustic sensing; the various actuator mechanisms for door and windows (deployed) (b) Overview of interactive canopy structure with an embedded capacitive sensor for controlling blinds. (c) Portable table with embedded pressure sensing for deployment.

at a structural scale using our processes and provide ways for designers to utilize them as actuators in interactive structures. In addition, we consider two technical evaluations, one measuring the accuracy of our swept frequency acoustic sensing gesture input approach (which relies heavily on a machine-learned recognizer), and a second evaluation which considers aspects of structural strength for these types of structures. Finally, we perform an informal gesture elicitation study and sketching session with subjects who are expert designers to explore the design space of interaction techniques opened by our basic input sensing methods.

Although we have constructed, and will briefly describe, a custom fabrication machine for our inflated structures, it should be noted that the focus of the work presented here is centered on engineering the collective capabilities emerging from sensing, actuation and construction methods, rather than the advances of the fabrication methods or any in-depth improvements of each individual technique.

We believe that collectively our sensing, actuation, and structure manufacturing methods provide a resulting system that demonstrates new and interesting HCI capabilities and present a viable path for manufacturing deployable smart structures with built-in interaction at room-scale. To illustrate this, we present three example objects that embed our proposed sensing and actuation capabilities – an interactive geodesic dome (described below), a responsive canopy and a deployable portable table (Figures 6.1 and 6.2).

6.2.1 Example: Interactive Geodesic Dome

As a motivating example, we now describe how our interactive geodesic dome structure works and various interactions with the structure. Additional examples are further described in detail in Section 6.5

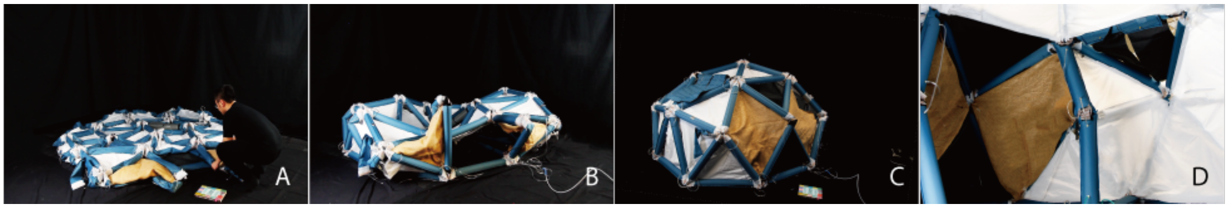


Figure 6.3: Shows a user connecting a pneumatic pipe (a) and the structure inflating itself (b) the structure is fully deployed (c) and the structure from inside (d).

Our geodesic dome consists of actuated doors and windows as well as acoustic sensors that can pick up user gestures as a part of the structure (section 6.2). Specifically, we perform swept frequency ultrasonic acoustic sensing by embedding contact microphones on the door and a support beam inside the structure. We are able to perform acoustic sensing for any truss member from a single point. We fabricate all our structures with inter-connected pneumatic truss members, allowing users to deploy large scale structure from a flat configuration by simply connecting an air supply (Figure 6.3).

After inflating the geodesic dome, the user performs a knock gesture on the door (Figure 6.4a). Upon the knocking, our sensing/machine learning pipeline recognizes the user's gesture and actuates the door, allowing the user to enter (Figure 6.4b).

After entering the door, the user squeezes (Figure 6.4c) an inflated member and our system is able to recognize the gesture and actuate windows by rolling them up (Figure 6.4d).

Similarly, if the outside environment gets dark, a user can perform the swipe gesture (Figure 6.4e), our system will respond by turning the lighting on inside the dome (Figure 6.4f).

6.3 Input Methods

In this section, we describe the various input mechanisms that can be embedded in inflated deployable objects in our system to support interaction. Our structures rely on a combination of input from acoustic, capacitive and pressure sensing. Our example applications integrate these input mechanisms into the structure for users.

6.3.1 Requirements for Sensing

The main requirements for integrating sensing with inflatable structures were (1) employing materials already in use, or readily adaptable to the production in this form, and (2) supplying a reasonably rich set of primitive, reusable, interaction techniques. We propose three types of sensing in this work: ultrasonic acoustic, capacitive and pressure sensing. The application of these methods (either individually or together) should be based on the context of use. For instance, pressure sensing needs regulated air pressure

Figure 6.4: (a) shows a user performing a knock gesture and our system recognizing user input; (b) shows the door opening for the user to enter.(c) shows a user performing a squeeze gesture; (d) shows the windows of the dome rolling up in response.(e) shows a user performing a swipe gesture; (f) shows the lighting switched on inside the dome.

to work well, whereas capacitive sensing can work well even in low pressure conditions. Similarly, in a noisy environment (such as sidewalks or roads with traffic) capacitive sensing may be favorable to using swept frequency ultrasonic acoustic sensing. However for situations/applications where inflatable objects are used in water (such as in a pool), capacitive sensing might not work. For more details on various application scenarios, please check section 6.7.2 for results from the design workshop. In the next section, we go over the engineering details of each sensing implementation.

6.3.2 Ultrasonic Acoustic Sensing

We implemented swept frequency ultrasonic acoustic sensing using an approach similar to SweepSense [125]. We use two small contact piezo elements that are affixed to the back of an inflated truss. One serves as a speaker and repeatedly emits a near ultrasonic frequency sweep (18 to 24 kHz within a 100 millisecond window) while the other acts as a microphone and receives the resulting attenuated signal. Depending on how the truss is manipulated, the internal configuration of the truss's cavity alters the attenuation of the signal at different frequencies as seen in (Figure 6.5).

We experimented with a number of gestures and found the most distinct responses came from a knock, squeeze, and swipe (Figure 6.5). From the responses, we extract a series of features: RMS, average power, the spectral center of mass, max/min index and values, standard deviation, and spectral band ratios. We then train a Sequential Minimal

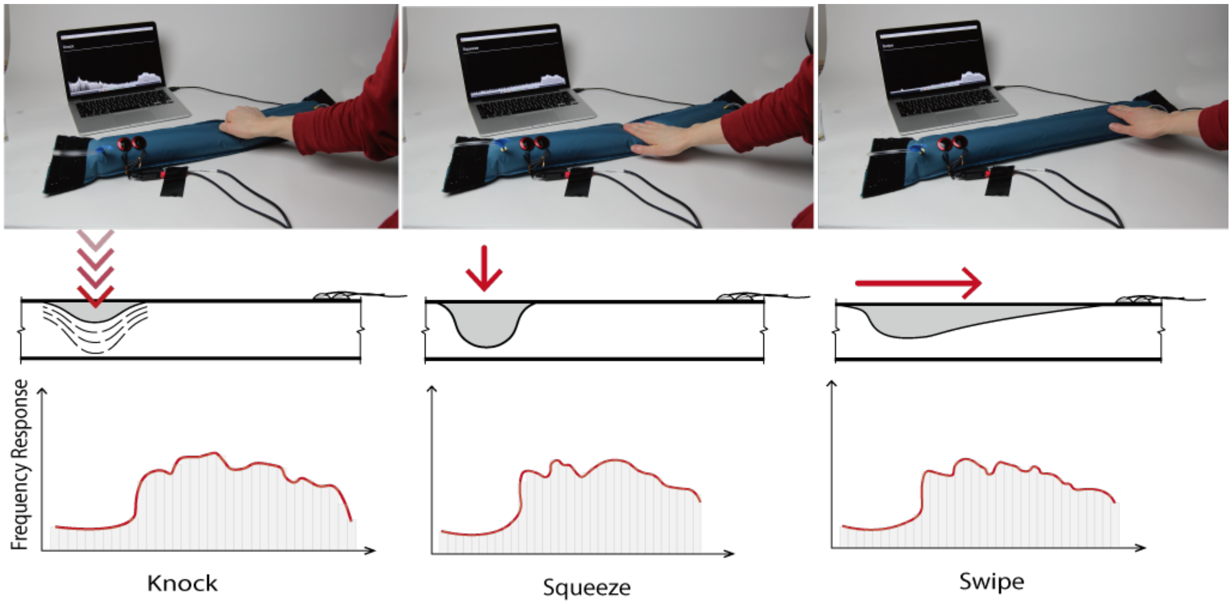


Figure 6.5: Using swept frequency ultrasonic acoustic sensing, we are able distinctly identify a number of gestures when performed on our inflated truss members. Note that the frequency responses above refer to the ultrasonic region (displayed in the far-right of the laptop screen).

Optimization-based Support Vector Machine (SMO-SVM) with default parameters using the Weka Toolkit. Our model is trained by capturing the responses on a single set of 10 trials for each of the 3 gestures. For more details on the classification accuracy please see the evaluation section below.

6.3.3 Capacitive Sensing

We implemented a capacitive sensor in the form of a touch slider by embedding 3M XYZ conductive tape [1] into our inflatable members during the fabrication process. As seen in (Figure 6.6a), we cut triangular patterns of 3M conductive tape and sealed it between our thermoplastic fabric layers. We further made connections between the tape and a metallic inlet valve by using silver epoxy. From the outside, we connected the valve to an MPR121 capacitive sensing board [2] (which has 12 sensing pins sampling at a rate of 29 Hz) controlled by an Arduino.

[1] 3M XYZ conductive tape: https://www.3m.com/3M/en_US/company-us/all-3m-products/~/3M-XYZ-Axis-Electrically-Conductive-Tape-9713/?N=5002385+3294001404&rt=rud

[2] MPR121 capacitive sensing chip: https://www.sparkfun.com/datasheets/Components/MPR121.pdf

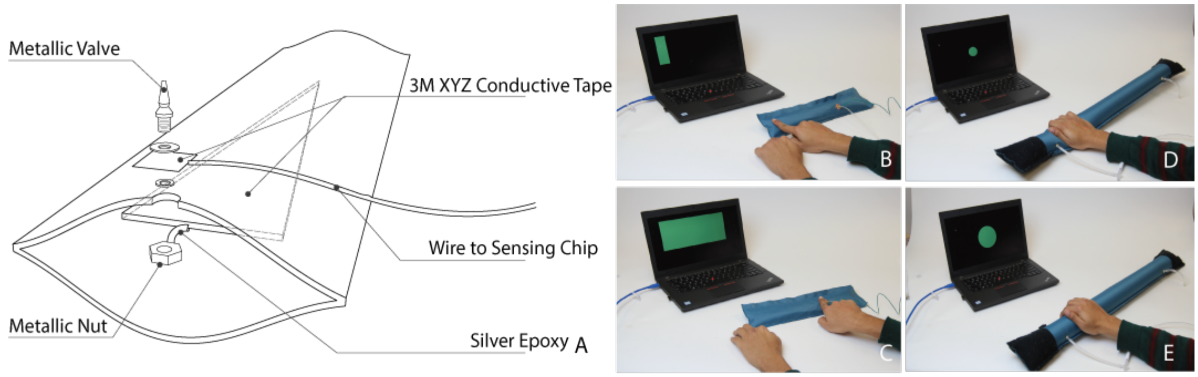


Figure 6.6: (a) Technical drawing of our capacitive slider implementation embedded into the inflatable member; (b) shows a user beginning their finger along the member; (c) shows the visualized output on a laptop display (d & e) Our pressure sensing implementation: as a user applies force to the inflated member and the pressure is visualized on the laptop display.

6.3.4 Pressure Sensing

We used an off-the-shelf pressure transducer (MPX57000-ASX[3]) for absolute pressure sensing. The sensor is able to detect the pressure changes in the range from 2.18 psi to 101.53 psi (15-700 kPa). We sense changes in pressure using an Arduino as seen in (Figure 6.6d & e).

6.4 Actuation Mechanisms

In this section, we describe the various structural mechanisms that can be used to embed actuation. We experimented with three different output mechanisms that can actuate as part of the structure (Figure 6.7). The first two mechanisms (inflated tendon and twisted tendon) are inspired by continuum robotics [196] where articulated joints are actuated with strings.

6.4.1 Inflated Tendon Drive

Our inflated tendon drive consists of a truss member which can fold when deflated, thus releasing the tension on a tendon. Upon inflation, the truss straightens out and pulls on the tendon (Figure 6.7c). The fixed length of the tendon string makes the structure move by a predetermined amount. This mechanism is used in the geodesic dome example to open and close the door.

[3]Pressure Transducer: https://www.nxp.com/docs/en/data-sheet/MPX5700.pdf

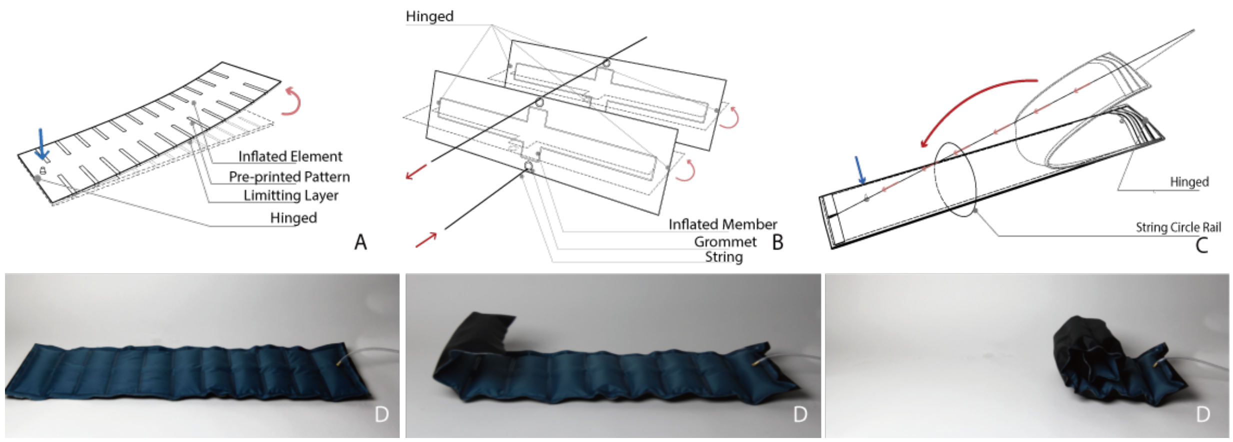


Figure 6.7: (a) rolling bend actuator implementations (b) twisted tendon drive, and (c) Our inflated tendon drive. (d) Our rolling bend actuator shown in bottom half rolling upon inflation

6.4.2 Twisted Tendon Drive

Twisted tendon drive is a combination of a tendon drive mechanism [196] with revolute joints. Typically, tendon drives are mechanisms that transmit motion through cables (only pull is possible through cables). In our specific implementation, the moment from the tendons is transferred to the joints which are located along the ends of the inflated members as seen in (Figure 6.7b). Since the joints are hinged, they act like revolute joints and allow the inflatable members to turn. This mechanism provides for variable actuation of the inflatable members perpendicular to their plane. To control the actuation, we simply move the tendon (or the string) attached.

6.4.3 Rolling Bend Actuator

We implemented a mechanism where inflation causes our fabrics to roll-up. We utilized the bending principle from Sheperd et al [208] to implement our mechanism. The printed mechanism consists of three layers of fabric, the first two layers are heat sealed in specific patterns (Figure 6.7a) to form inflatable pouches as seen in (Figure 6.7). The third layer is attached to the bottom of first two layers and acts as a strain limiting layer.

The direction of the bend will be away from the strain limiting layer, with each pouch contributing to the roll by pulling its neighboring pouches closer on the opposite side. The roll up can be seen in (Figure 6.7). Each pouch can bend to a 75 degree angle (max), with standing pressure up to 16 PSI. The actuator was initially 33 inches long, shrinks to 23 inches.

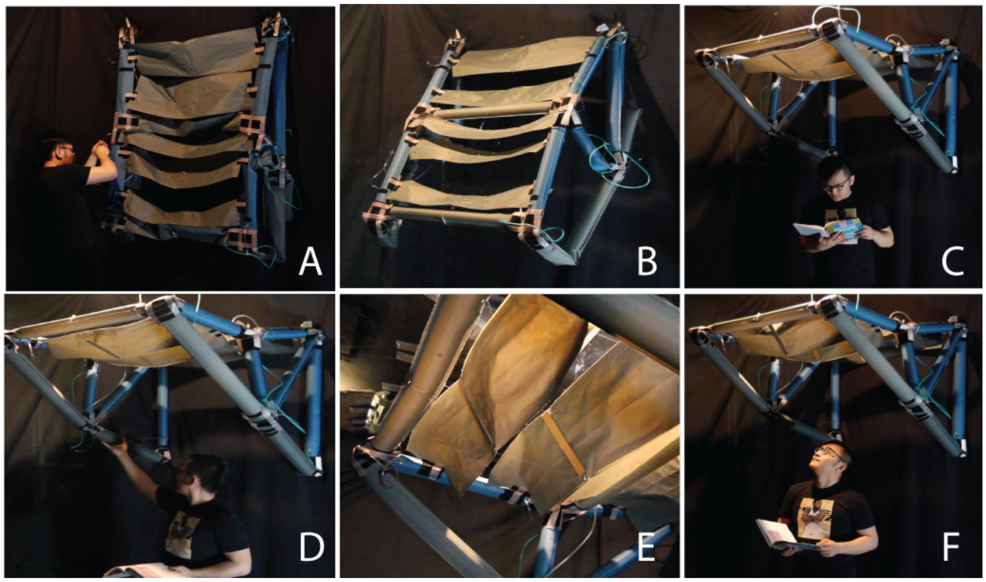


Figure 6.8: A walk-through of our interactive canopy with a user deploying it (a-b) and controlling the blinds via a swipe gesture (c-d) to receive more light (e-f).

6.5 Additional Example Structures

In this section, we show a few more additional demonstrator applications we developed by using the above input and actuation methods. First, we will walk through an interactive canopy with an embedded capacitive slider to control the blinds and a simple portable table that is deployed on pressure input.

6.5.1 Deployable Responsive Canopy with Variable Blinds

Our canopy consists of multiple truss frames connected to each other with inflated members. When deployed the canopy is 1m tall, spans 1m wide and stretches forward for 2m (section 6.2). The roof of the canopy consists of variable angle blinds, controlled by a twisted tendon drive actuation mechanism. The bottom truss member is embedded with a capacitive slider sensor to support user input (section 6.2). To deploy the canopy, the user first hangs it as desired and makes a pneumatics connection (Figure 6.8a). Upon inflation, the canopy deploys itself (Figure 6.8b). Once fully deployed, the canopy provides a shade under which the user can stand and e.g., read a book (Figure 6.8c). The user then manipulates the embedded capacitive slider (Figure 6.8d) on the truss member to control the amount of light. With the help of the twisted tendon drive mechanism, the blinds open (Figure 6.8e) e.g., to let more light in (Figure 6.8f).

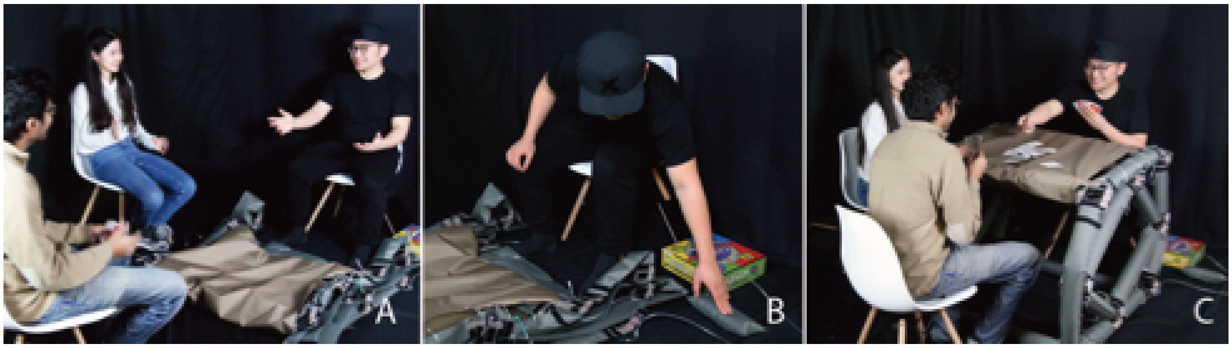


Figure 6.9: A deployable table with a user triggering the structural members' inflation with an embedded pressure sensor.

6.5.2 Deployable Portable Table

As a final demonstrator application, we implemented a deployable table with an embedded pressure sensor (Figure 6.9). First, we fabricated truss frames on both sides and connected them with beams to form our deployable table. When a user steps on the leg (truss member) of the table, the truss members acts as a pressure sensor and the system simply senses the pressure change and triggers itself to deploy to inflation. The deployed table is 1m tall and 1m wide (section 6.2) and is large enough to support multiple users sitting around it (Figure 6.9).

6.6 Fabricating Pneumatic Trusses

We employ a printer design for heat sealing fabrics that is similar to the designs from Aeromorph [170] and Printflatables [202]. To print custom truss members, we fit a narrow heated rod (implemented using a soldering iron) to the motion platform of a modified Cartesian 3D printer with an extended 4 feet by 1 foot fabrication area as illustrated by (Figure 6.10a). The printer applies heat at a constant rate to seal TPU-coated fabrics forming an inflated bladder. All examples use 200 Denier[4] Oxford heat-sealable cloth.

6.6.1 Design Workflow

We used the Rhinoceros CAD system (Rhino) with the Grasshopper visual programming plug-in to model our truss frames. All of our truss examples—dome, canopy, and table—were modeled using built-in sketching features such as line and poly-line to design a 3D model of a truss frame. Once an initial model was established, we verified the structural performance using Finite Element Analysis (FEA) with the Karamba3D plugin and performed several iterations (manually) by changing triangle lengths/arrangement (along with FEA) to arrive at a final design. We then used Silkworm (Rhino plugin) to generate

[4] A Denier is a unit of measure for textiles which refers to linear mass density of fibers.

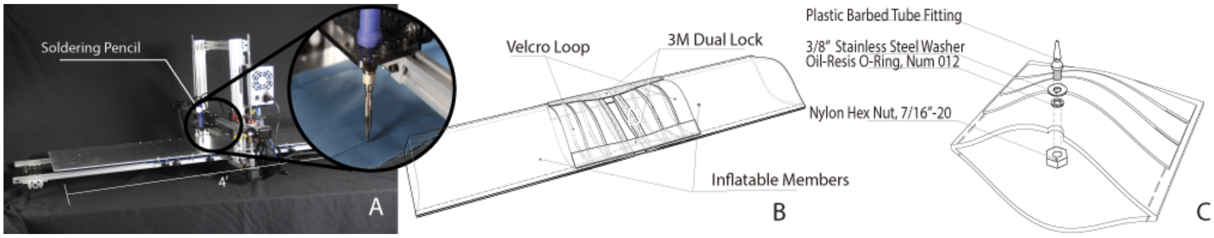


Figure 6.10: (a) Our customized heat sealing printer; Working condition of the soldering iron can be seen through inset. (b) Joints made between inflatable members with velcro hook and loop. (c) Exploded view of the composition of the inlet valve system.

G-code paths for specific lengths of truss members. Once G-codes were generated, we fabricated the individual members using our custom printer. In the future, automatic support (with a design tool) can help in minimizing design iterations involved in finding the optimal configuration (length of truss members) while automatically checking for stability with FEA.

6.6.2 Making Joints and Connections with Inflated Members

We experimented with various mechanisms for forming joints between our truss members. The main criteria for forming our joints include making them lightweight so that they are able to move the members in the air. We investigated CNC machined foam blocks as a way of digitally fabricating the joints. However, we found that joint using hook and loop fasteners (Figure 6.10b) performed better as they are able to resist tension and still provide one-degree-of freedom revolute joints.

We used the 3M dual lock SJ3571[5] as a loop and the 3M (Type 250) SJ3552CF [6] as a hook component to form our connections (Figure 6.10b), providing a 12 in 2 contact area. Based on the data provided by the manufacturer, the hook and loop fasteners can resist 2.2 lb of lateral force per square inch away from each other. Thus, with this contact area, we estimate each of our joints is capable of bearing a 26.4 lb tension load.

6.6.3 Installing Valves and Interconnected Tubes

All our inflated members are made with inlet valves, hex nuts and washers (Figure 6.10c). Further, each of our truss members (5 inches wide) is installed with multiple valves and share a single pathway for air to allow inflation of the whole structure from a single point. However, with larger structures, such as the geodesic dome, we observed that providing multiple pathways for air and sequencing the airflow results in faster deployment. Our

[5] 3M dual lock SJ3571: https://multimedia.3m.com/mws/media/107979O/scotchmate-reclosable-fasteners-sj3571-and-sj3572.pdf

[6] 3M (Type 250) SJ3552CF: https://multimedia.3m.com/mws/media/349929O/dual-locktm-reclosable-fasteners-sj3551-sj3552-sj3550.pdf

geodesic dome has six pathways of air while other examples (canopy and table) each have two pathways for air.

6.6.4 Pneumatic Control System

We used a Dewalt stationary air compressor that can reach up to 165 psi and has a tank storage capacity of up to 6 gallons. We sensed the air pressure in the entire structure using a pressure sensor and regulated air passage 12V DC solenoid valves. Further, we used a simple bang-bang control method for regulating the air pressure. Similarly, for actuation system, we used 12V DC solenoid valves controlled by an external power supply and an Arduino for digital logic. The pneumatic control system is connected to our input sensing/machine learning pipeline and responds to user action by controlling the solenoids.

6.7 Evaluation

We performed overall three types of evaluation: Sensing Evaluation, Design Workshop, and Strength Evaluation. As a part of our sensing evaluation, we chose to only evaluate ultrasonic acoustic sensing since it has never been implemented on inflatable objects and its robustness has never been studied on inflatable objects. Whereas other types of sensing techniques like capacitive and pressure sensing have been thoroughly studied in HCI literature [82] but missing engineering implementation with inflatable objects which we provide (section 6.3.3 and 6.3.4). Second, we follow up the sensing evaluation with a design workshop consisting of an informal gesture elicitation and sketching session with subjects who are expert designers. The overall goal of the design workshop is to uncover existing affordances with deployable structures and to generatively brainstorm novel uses that users are interested in exploring or building. Finally, we perform a preliminary strength analysis of our inflated truss structures to illustrate the approximate load bearing capacity of our structures. Combined together all these evaluations provide a design knowledge on choosing the type of applications when designing a new interactive deployable structure.

6.7.1 Sensing Evaluation

We evaluated the gesture recognition rates of our swept frequency ultrasonic acoustic sensing in the inflated trusses through a small user study consisting of 12 participants (8 male / 4 female; mean age: 27.33; age standard deviation: 3.23). All our participants were students at our university recruited through word-of-mouth.

We inflated a single truss member and attached two contact piezo elements at one end of the truss. The inflated member was affixed at each end to the table to simu-

Performed Gesture			
swipe	*knock*	*squeeze*	**Classified Gesture**
84	1	3	*swipe*
8	93	3	*knock*
6	6	94	*squeeze*
2	0	0	*no interaction*

Table 6.1: Confusion matrix (in percentages) for our cross-user swept frequency ultrasonic acoustic sensing user study. Our model was trained on a single user and tested with 12 participants for 360 trials in total. The classifier obtained an overall accuracy of 90.33%.

late its placement in a structure and to maintain a stable interaction surface between users.

We trained a single model using ten samples for each gesture (swipe, knock, and squeeze), in a noisy and high traffic lab space. Additionally, we trained a null state (no interaction) during which there was no interaction with the inflated member, resulting in four possible classes for the classifier.

We evaluated the classifier on the 12 participants with no additional training from the participants. Each participant performed each gesture (knock, swipe, and squeeze) 10 times in a random order amounting to 30 trials per participant, and 360 trials in total. Prior to the study, participants were only told the name of the gestures and then asked to perform each gesture according to its name.

We found some participants swiped rapidly a single time, while others swiped slowly and multiple times (appearing to be more of a rub). Similarly, when knocking some participants knocked very hard once or twice while others knocked more gently for five to six times. However, these variations in gesturing across users had little effect on our model. As seen in Table 6.1, our classifier obtained an overall accuracy of 90.33%. In one instance, a participant performed two swipe gestures that were not recognized (*i.e.*the classifier returned no interaction).

This was due to the user not applying enough pressure on the truss during the gesture to change the frequency response. The relatively high accuracy of our single generic model with minimal training suggests this sensing technique is well-suited to support new and different users interacting with these deployable structures without individualized training.

6.7.2 Design Workshop

We conducted an informal gesture elicitation [255] session in order to explore the interaction technique design space opened by our basic input sensing methods and to better understand whether this basic gesture vocabulary provides a good basis for building larger interactions. In the second part of the design workshop, we invited participants for sketching sessions with subjects who are expert designers. The goal was to judge whether participants could create diverse scenarios in which interactive deployable structures could be used along with their interaction. During the second part, the participants were free to sketch.

Participants:

We recruited 5 participants from our university (2 male, 3 female, aged 27-35). Two majored in design, 1 in architecture and the other two had professional industrial design backgrounds. All participants reported to have been using mobile phones/tablets with gesture uses every day except one participant said he uses gestures uses 2-3 times a week. All participants also reported having sketching experience.

Tasks & Procedure:

The workshop took place in our research lab and lasted between 30 and 45 minutes for each participant. Participants were given empty sheets or paper, pencil and single inflated member. To begin, participants were given an introduction into the project by the experimenter on some basic understanding of what deployable structures are and were shown various parts of the structures that can actuate. The participants were instructed to only perform gestures or interactions on the inflated member given and were asked to think aloud when performing gestures. Participants were shown 3 pictures of interactive tasks from the examples ((section 6.2) and (section 6.2)) available in the paper namely – 1) geodesic dome door opens upon input (Figure 6.4 a & b) 2) window of the dome rolls after input (Figure 6.4 c & d) and 3) controlling the blinds of the canopy (Figure 6.8) using input. Note that in all three of these pictures of interaction, we masked the user performing input using a gesture. We only showed pictures of the structure and their desired responses such as door opened, window opened or shades rotated, etc. For each interaction, we asked users to perform 2-3 gestures on the inflated member and point to the part of the structure would they perform the gesture on. After finishing the gesture elicitation, we showed participants the video of our system with various inputs, outputs and interactions along with three examples (Figure 6.2) we constructed, we then asked them to generatively come up with 2-3 new designs of interactive deployable structures by sketching them.

Gestures Analysis:

Participants proposed a total of 40 interactions for the 3 referents – opening the door, opening the window and controlling blinds, 30 of which were distinct (considering dis-

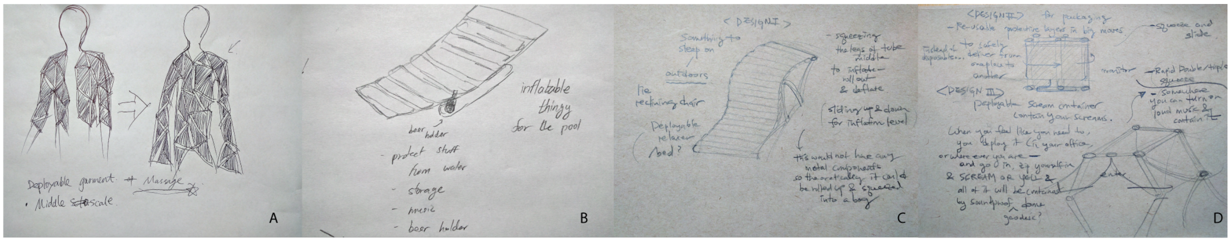


Figure 6.11: Shows various user sketches of interactive deployable structures a) Shows a deployable vest that can custom fit upon input b) shows a floating pool chair with adjustable storage closet c) shows a chair with adjustable backrest d) shows various other interactive deployable structures

tinctness on a per-referent basis). Specifically for opening the door, in total 15 gestures (11 distinct) were proposed, for opening a window – 11 (9 distinct) were proposed and controlling blinds – 14 (10 distinct) were proposed. Most popular among overlapping gestures were – for opening door was tap multiple times (2/total) and squeeze (2/total), popular for controlling blinds is slide/swipe (3/total) and for opening windows of the dome there was no clear majority consensus.
We observed three main themes in gestures: participants sometimes used - multiple hands to engage in interactions, performed input on multiple inflated members sequentially and combined two gestures at once – e.g., press and slide. Most of these interactions can be already supported by one or more input methods proposed in the paper. For instance squeeze and slide can be implemented by combining pressure and capacitive sensing together. Similarly interacting with multiple inflated members at once can be sensed using pressure sensing.
Participants observed that different parts of the structure afforded different interaction. For instance P2 mentioned "I'm more comfortable performing these gestures (showing the gesture) inside than outside since people are able to see me", similarly, P4 mentioned that "squeeze is better afforded in this part (pointing) to the structure, since there is a hanging inflated member rather than inflated member attached to the structure". These reactions suggest that participants are selective about which parts of the structure they want to interact with.

Sketches of Interactive Deployable Structures:

After watching the video of interactive deployable structures, showing various input, output and construction possibilities, we asked participants to brainstorm and sketch 2-3 designs they were interested in building. The majority of the participants proposed at least 1 water based interactive deployable structure that they could build. For instance, 2/5 participants suggested inflatable pool chair that has a storage closet that can be deployed for drinks (Figure 6.11b). Other water-based inflatable interactive structures were a boat that had interactive control for rudder, swimming safety ring, an inflatable interactive hammock, interactive deployable fishing net that transforms to catch a fish,

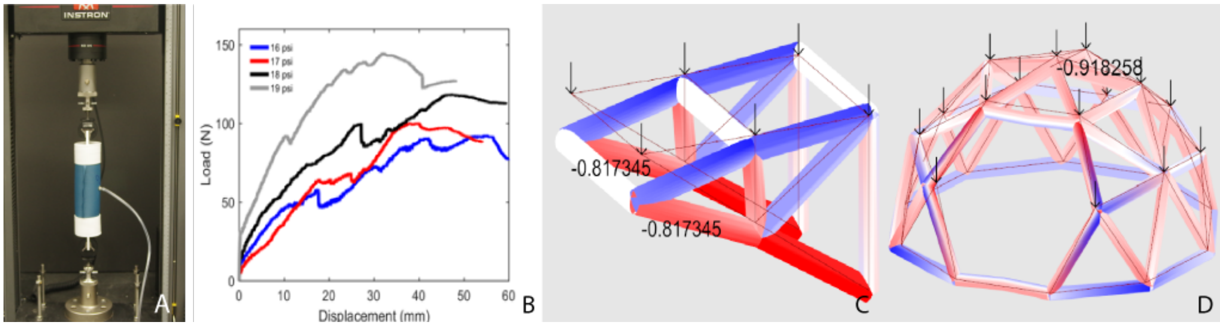


Figure 6.12: (a) Compression testing of an inflated truss member with an Instron 5969 testing machine. (b) Shows loading vs applied pressure behavior of truss elements under compressive load. (c) FEA analysis depicting the deflection of our truss frames from undeformed state. (d) Dome shows a deflection of 0.92cm from top and canopy shows a deflection of 0.81cm from tip of the roof.

chair that has an adjustable backrest (Figure 6.11c) , deployable garment (Figure 6.11a) that can custom fit itself, etc. Below are some of the sketches of what participants wanted to build.

6.7.3 Strength Analysis

In order to assess the structural strength of our prototypes, we performed finite element analysis (FEA). To perform FEA, we first gathered the material properties such as elastic modulus (a measure of the intrinsic stiffness of material) by performing compression analysis using a universal testing machine (Instron 5969) on truss elements (Figure 6.12a).

We compressed our truss members at different pressures: 16, 17, 18, and 19 psi (max). Our experiments (Figure 6.12b), reveal that at 19 psi pressure the truss element can carry up to 142 N load before buckling while this maximum load drops to 91 N at 16 psi pressure. Hence, we recommend that the truss members be maintained at 19 psi for maximum load bearing strength and utilized the elastic modulus at 19 psi for our FEA modeling.

To further proceed, we used Karamba3D software package along with Grasshopper to model and perform our FEA analysis. During the modeling, we assumed all our members are connected with revolute joints, which allow members to rotate around the joint but otherwise constraints relative movement. Based on these assumptions our truss structure allows truss members to bear only axial loads, rather than bending or torsion.

Finally, to find the maximum load of the entire structure can bear before reaching the maximum deflection, we first referenced the International Building Code[7] for maximum

[7]International Building Code 2017: https://codes.iccsafe.org/public/document/toc/542/

deflection criteria. The code gives specific evaluation schemes for our structures: L/360 (floor structure) and L/180 (roof structure), where L is the diameter of the dome and in the case of canopy it is the length of the roof.

Applying these criteria over the dimensions (the diameter of the dome is 3.3m and the length of the canopy is 2.9m) gives us maximum allowable deflection of 0.92cm for the dome and 0.81cm for the canopy (Figure 6.12 c). We used these two criteria to find the maximum load for both our structures.

During our analysis, we applied simulated point loads to the joints of the canopy and the dome. In the results of FEA analysis, as seen in (Figure 6.12 d), the members in tension are rendered in blue and compression are rendered in red. Further, the deformation of the shape is compared with the original shape (represented as solid lines).

Maximum deflection is displayed in centimeters. This analysis predicts that the dome can bear 7.6kg (507g at each joint) and the canopy can bear 1.88kg (313g at each top joint). While this analysis is in no sense complete, it indicates that acceptably strong structures can be fabricated with these techniques.

6.8 Limitations and Future Work

Our work shows a range of techniques that enable the custom fabrication of room-scale deployable pneumatic structures with integrated input and actuation capabilities. This approach opens up many new opportunities. However, it also has limitations. For example, while we are able to assemble trusses of arbitrary sizes from shorter trusses (limited to by the length of our printer), the effort involved in assembly depends in part on the printer size. One way to address this limitation is to further automate the joinery of inflatable truss members. Also, in all our examples and prototypes we used a regulated pressure set-up with constant air supply to keep the structures intact. One way to eliminate the need for pressure regulation is to use a rigidization strategy such as injecting foam throughout connected members to form the final shapes. We are also interested in examining how wrapping our inflatable members with fiber-reinforced composites and curing them on-demand can be used to rigidify the structure.

6.9 Summary

In this chapter, we explored the design space of deployable pneumatic structures with integrated interactive capabilities that can be digitally fabricated at room-scale. We specifically looked at embedding three types of sensing in our objects – acoustic, capacitive and pressure, to provide diverse forms of input. Our example prototypes such as a geodesic dome, canopy, and portable table demonstrated how users can leverage these interaction possibilities as part of an environment which is responsive to human input. Further, our structural analysis (FEA) indicates that our structures can handle overall loads of 7.6 kg for the dome and 1.8 kg for the canopy. Finally, our lab-scale study on the inflated truss members revealed that we are able to classify gestures such as knock, squeeze, swipe and no interaction with an overall accuracy of 90%. Furthermore, an exploratory design workshop conducted with users provided a pathway to understand whether the basic gesture vocabulary proposed forms good bases for larger interactions and design space. From sensing to actuation, we have demonstrated an approach to fabricating room-scale, deployable pneumatic structures that possess interactivity which is fabricated as part of the object. Our work builds on prior efforts related to deployable and relocatable objects and allows for human interaction to take place on these structures in a big way.

Chapter 7

Computational Wood

In the preceding chapters, we looked at approaches that enable us to manufacture computational material devices in a built environment with capabilities ranging from sensing to actuation. These capabilities were developed to support interaction in various infrastructure materials such as composites, concrete, plaster, geotextiles, etc. However, wireless communication and interaction with infrastructure materials are still missing. In this chapter, we explore how to manufacture *wood* with inherent wireless capabilities such that products, when made with wood, can sense interactions and enable wireless interactivity. In addition, this chapter also contributes to "battery-free" sensing for human interaction with wood.

7.1 Background and Motivation

Today, unsustainable materials from the built environment alone account for up to 20% of global greenhouse gas (GHG) emissions worldwide. In response, many architects, engineers, and designers around the world are adopting sustainable materials to manufacture the built world. One common material currently being adopted on the mass scale is *wood*. In addition to having benefits for the environment, building with wood enables us to create a physically, psychologically [162], and aesthetically healthy built environment.

Trees and lumber have been used for building structures since prehistoric times. Still, in North America in particular, the adoption of lumber took off in the late nineteenth century and the beginning of the twentieth century as a construction material due to the vast resources of lumber in the Pacific Northwest. However, after disasters such as the Great Chicago Fire [55], wood was perceived as unsafe, and the use moved towards concrete and steel.

Recent advances in fire retardant treatments and, more importantly, a novel way of manufacturing wood called cross-laminated timber (CLT) has put the material back in

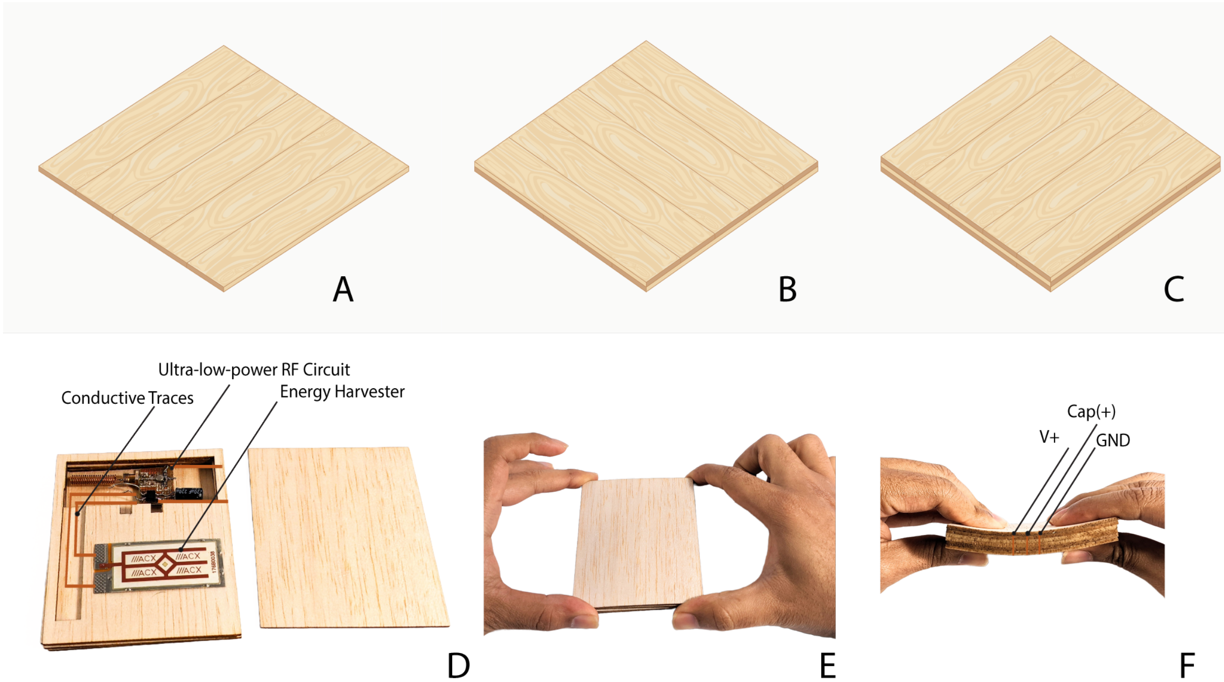


Figure 7.1: Shows the manufacturing process for computational wood, a six layer cross laminated ply of a relatively soft wood with embedded circuits and piezoelectric energy harvester

the spotlight. Building with wood is now safer, more sustainable, and is being adopted vigorously. In this chapter, we explore the possibilities of enabling wood to be innately interactive, so that designers and engineers can build wirelessly connected digital surfaces and objects made of wood. Additionally, our goal is to enable interactivity in wood in a battery-free sustainable manner, as batteries contribute to electronic waste, are toxic, and require periodic maintenance when deployed in the infrastructure.

Besides sustainability & maintenance considerations, as a structural material, wood offers tremendous possibilities for customization, since it enables computer numerical control (CNC) machines to allow precision cuts. This allows designers to embed interactivity in a more planned manner. For instance, interactive doors and windows could be manufactured with circuits and sensors to exact specifications (prefabricated) and assembled with very little labor.

7.2 Computational Wood

In this work, we introduce computational wood, a new type of wood that enables battery-free wireless sensing and interaction. Traditionally, plywood is manufactured by laminating thin layers or "plies" of wood veneer together with adjacent layers with their wood grain rotated up to 90 degrees (Figure 7.1 A, B, C) from each other to create a flat sheet. This process naturally lends itself well to inserting computational elements between the plies. We exploit this process to embed energy harvesters and interactive circuits to enable battery-free sensing. In particular, we embed piezoelectric material such that bending or any mechanical transduction within wood generates tiny amounts of power. Once enough power (microwatts) is harvested, it can be used to power an RF circuit embedded within layers of wood to wirelessly communicate about interactions with the material.

In this chapter, we first describe our processes for manufacturing computational wood, including the various ways in which energy harvesting mechanisms are embedded to generate power for battery-free communication. We then move on to introduce our new ultra-low-power RF circuitry, which is used for sensing and communication. We discuss our target spectrum and the broadcast frequencies where our RF circuitry operates. We demonstrate a range of interactions with objects manufactured in computational wood. For example, we show a drawer, a door handle, or even input controls that are entirely made with computational wood so that interactions with these objects, such as pulling a drawer or opening a door, can be detected wirelessly in a battery-free manner. Next, we evaluated the power budget required to operate our computational wood devices with embedded harvesting mechanisms and circuitry. We characterize the bandwidth needed & the maximum number of concurrent device usages that is possible. Finally, we discuss the sensing range in which our computational wood devices operate and the different environments in which they can detect interaction wirelessly.

7.3 Manufacturing Computational Wood

We now walk through a simple example explaining how computational wood works. Consider a block of wood as seen in Figure 7.1 F, which is a 6-layer ply of relatively soft wood (Balsa). As we see in the cross-sectional view in Figure 7.1 D, here, the piezoelectric material and an ultra-low-power RF circuit are embedded within a 6-layer ply. The conductive traces from the piezoelectric material lead up to the RF circuit and finally to the edges of the block. There are three leads that emerge from the edges of the block, v +, cap (+), and GND. (Figure 7.1 F).

Mechanical bending of the wood block, even a few degrees (<5 degrees), causes piezo energy to be harvested. The energy collected is stored in a capacitor in an RF circuit. Once enough energy is harvested, it can be used to power an RF broadcast with a mechanical switch. For example, a piece of conductor that mechanically touches two traces v+ and cap (+) at the edge of the wood block.

In the above example, energy is harvested by direct mechanical transduction of wood (i.e., bending of the wood by the user). This method helps generate energy from many of our daily interactions with wood. For example, walking, tapping, or stepping on wood panels will cause them to bend.

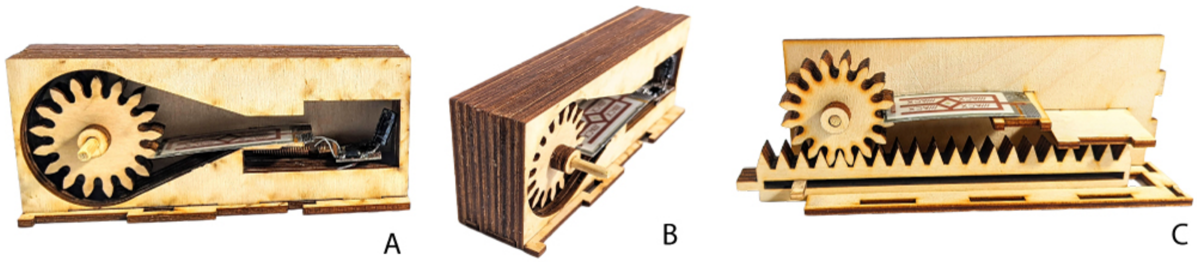


Figure 7.2: Shows various energy harvesting mechanisms that are embedded within plies of cross laminated wood

7.3.1 Energy Harvesting Mechanisms

In addition to direct mechanical transduction on wood, we also introduce methods that use mechanisms embedded within the layers of manufactured wood. For example, as seen in Figure 7.2 A, a gear mechanism is embedded such that the gear rotation hits the piezo material within the wood to generate energy.

Similarly, an embedded rack & pinion mechanism (Figure 7.2 C) could transduce a linear motion with manufactured wood to generate energy. For example, moving a piece of wood horizontally could generate energy.

We envision these mechanisms being manufactured and integrated into wood products such as drawers, doors, etc. (as seen in Figure 7.10) to allow everyday household wooden objects to generate energy from human interaction.

7.4 Functional Circuitry

The underlying ultra-low-power RF circuitry that is embedded between layers of wood has three main components: (i) energy harvesting and storage, (ii) A Tunnel Diode Oscillator (TDO) with a tank circuit, and (iii) mechanical switch that turns on the oscillator when the human interaction occurs. Now, we go over the details of each of these circuits in detail.

To harvest energy, we used a piezoelectric material (PZT), a ceramic perskovite embedded between the mechanisms and the layers of wood. The energy extracted from the piezo source is AC, therefore, is rectified using an ultra-low voltage rectifier (d1,d2,d3,d4) (Figure 7.3) and stored in a 220 uF 25V capacitor.

Once enough threshold energy is reached, the energy can be released to the second stage of the circuit due to a mechanical action of the wood by the user, e.g., a wooden drawer reaching a final position when pulled (see Figure 7.8 A).

The second stage of the circuit(Figure 7.3) consists of an ultra-low-power tunnel diode oscillator (TDO) circuit.

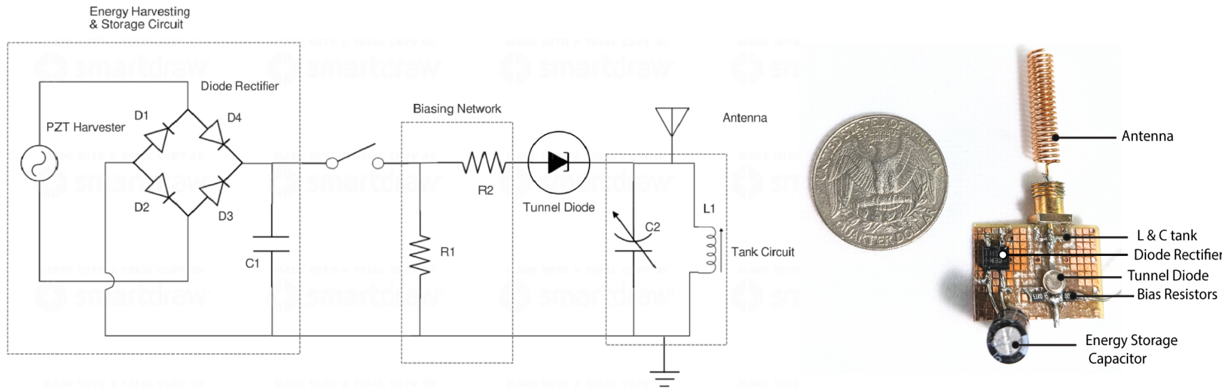


Figure 7.3: Shows energy harvesting, storage and ultra-low-power RF circuit constructed with tunnel diode

7.4.1 Tunnel Diode Oscillator

A tunnel diode is a two-terminal p-n junction diode that has an extremely high doping concentration at the junction. High doping concentration causes a very thin depletion region, demonstrating a quantum tunneling effect. Therefore, tunnel diodes exhibit a characteristic negative resistance curve; for example, as we increase the voltage of the tunnel diode, we can see (Figure 7.4A) that the current through the device decreases. The negative resistance region makes it possible to design high-frequency RF circuits at extremely low power. In this project, we used a tunnel diode AI101A due to its low peak voltage of 160 mV and peak current consumption of (0.75mA). If we bias the tunnel diode to operate in this negative resistance region along with an LC (l=33nH,c=1.3Pf-3.3pf) circuit, then we can build an ultra-high frequency oscillator that operates at only 120 microwatts biasing power. In addition, we offer a variable capacitor c2 (1.3Pf-4.6pf) to tune the output frequency of the oscillator to the desired frequency.

The tunnel diode oscillator IV curve, as seen in Figure 7.4, operates as follows. Initially, as the voltage of the diode (Vd) increases, the current increases, and when Vd is greater than the peak point voltage (point A in the graph Figure 7.4 to the left), the diode is driven into the negative resistance region. In the negative resistance region, the current wants to drop as we increase the voltage, and at this point, the change in slope of the current will cause the inductor L1 to react by trying to maintain the current flow. This causes the voltage to slam to the point B (in Figure 7.4), extremely fast. Now, at point B, the voltage is higher than Vd; therefore, the current drops to reach the valley point C in Figure 7.4. Again at point C, as the voltage tries to drop further, we start hitting the negative resistance region, and again the inductor L1 resists the change of slope in current. This causes the voltage to drop to point D on the IV curve. From point D, the voltage starts to increase, and the process repeats by continuing to bounce around points A, B, C, and D in the IV graph to produce oscillations.

Finally, as seen in the IV and PV graphs Figure 7.4, the threshold voltage needed to

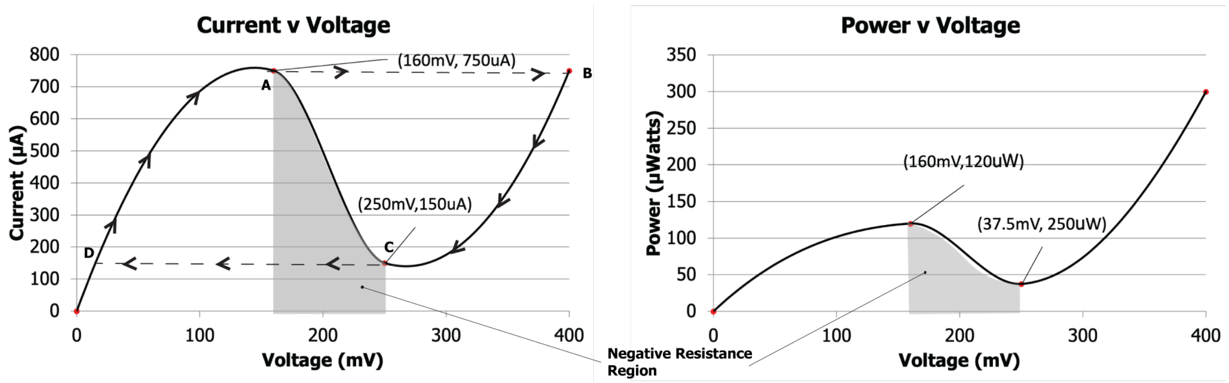


Figure 7.4: Shows current vs voltage and the power vs voltage graph for biasing the tunnel diode in the region of interest

activate our tunnel diode oscillator is above 160 mV, a peak current of 750 uA, and a peak biasing power of 120 uW.

7.4.2 RF Broadcast

After building our ultra-low-power oscillator, our next task is to identify the RF spectrum to target and operate the device.

Broadcast frequency

Our main design challenges in identifying the broadcast frequency were to ensure that the antenna sizes were small enough (15-18cm) to work with for embedding within the wood. The frequency of operation is directly related to the antenna sizes based on antenna theory. For instance, to operate in the VHF range (30 MHz - 300 MHz), a quarter-wave monopole antenna needs to be 238 cm - 23.8 cm, i.e., the antenna sizes are inversely proportional to the operation frequency. Hence, to satisfy our design constraints of being able to embed antennas of lengths 15-18 cm, we need to operate above 395 MHz.

Besides looking at antenna sizes for embedding within the wood, another area of concern is signal propagation characteristics within different environments (such as buildings, walls, etc.). Extremely high-frequency UHF signals tend to bounce off obstacles rather than penetrate them, so we decided to target the lower end of the UHF spectrum from the 395-600 MHz range.

Spectrum Sensing and FCC compliance

After identifying the target frequency range, we wanted to ensure that we complied with the FCC Part 15 transmitter regulations [20], and that we did not interfere with existing spectrum usage. We further considered the environments in which our compu-

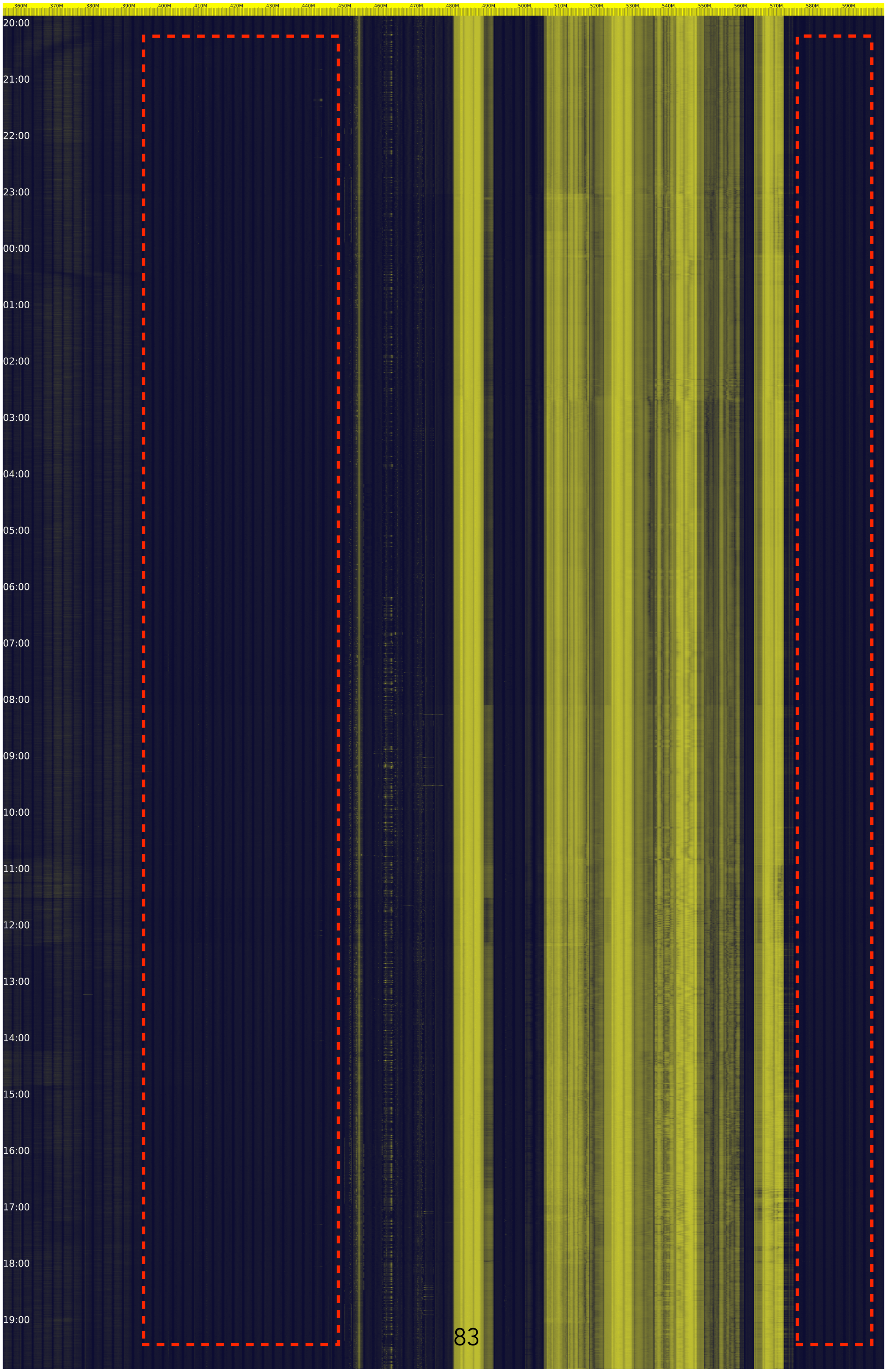


Figure 7.5: A 24-hour spectrum data for 350MHz-600MHz. The dotted red line indicates quite parts of the spectrum that can be used for sending broadcasts

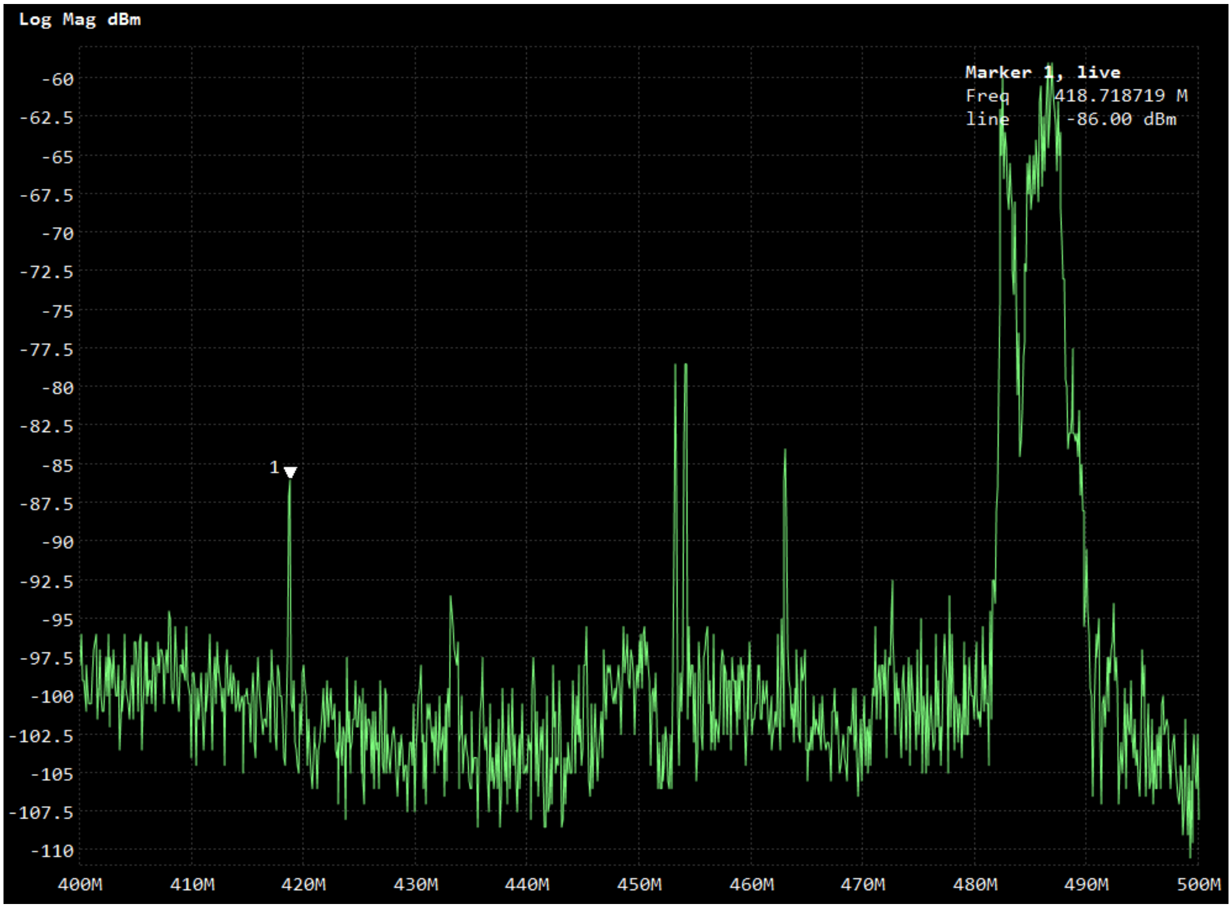


Figure 7.6: Power spectrum of our oscillator peak at 3m distance. We generate a signal in the 418 MHz band, at a peak biasing power of 120 µW.

tational wood objects might operate (e.g., residential and commercial buildings). We performed spectrum sensing in the range of 350 to 600 MHz, with 50 kHz steps, each using a wideband antenna and an SDR device. We collected data for 24 hours in an apartment complex. The results of the power spectrum can be seen in Figure 7.5. Our analysis indicates that the spectrum from 350-390 MHz is lightly occupied, while 480-490 MHz & 505-560 MHz are densely occupied, 455-480 MHz is moderately occupied, while 395-450 MHz & 575-600 MHz parts of the spectrum are relatively unused and are ”quiet”. However, we also note that in the bands of interest, 400-410 MHz, only spurious emissions are allowed by the FCC. Although conditions may vary, we can expect similar results in many locations in the region tested.

In addition to spectrum sensing, to comply with FCC part 15 power requirements, any part-15 transmitter must have radiated power within the defined limits. In the frequencies of interest for us, the field strength allowed by FCC for transmission is 200 µV/m @ 3 m; this is equivalent to -50dbm of transmitted power, assuming a transmit antenna gain of 1 dBi. Although we indicate the transmitted power in dBm, we note that the

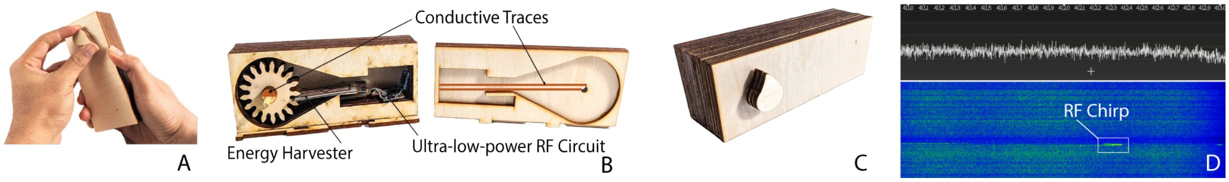


Figure 7.7: Shows handheld interactive input control device made from wood, rotating the knob by 180 degrees, sends a wireless event

quality of the antenna match determines the compliance. For instance, a transmitter with very low power output (in the microwatt range) could be matched with a very well-constructed antenna and would probably violate the FCC. On the other hand, transmitters that have a relatively high power output (perhaps 10 milliwatts or 1/100th of a watt) but an intentionally poor antenna system can achieve the 200 uV/m ratings.

Therefore, we used a Rhode & Schwarz field strength power estimator to calculate the required values. Then, using the TinySA spectrum analyzer [26], we measure our actual emissions at a distance of 3 m from the transmitter. As seen in Figure 7.6, our transmitter has an effective isotropic radiated power (EIRP) of -86 dBm at 3 m, which is less than the allowed -82.9 dBm (200 μV/m @ 3 m).

7.5 Example Applications of Computational Wood

In this section, we go over many examples of applications of manufacturing objects with computational wood and the interactive applications they enable.

#1 Interactive wood controls

In the first example, we manufacture a handheld interactive control device made of wood. This example uses an embedded gear mechanism within the wood plies. The gear mechanism is placed so that when a user rotates the input control (Figure 7.7), the gear hits the piezo material embedded within the wood to generate power. A cross-sectional view of the laminated wooden device can be seen in Figure 7.7. When enough power is generated, it is harvested and stored in the capacitor of the RF circuit. When the user completes the interaction (i.e., rotating the knob), the conductor on the gear rotates along and acts as a switch, connecting the two traces (see Figure 7.7 B) that run between the capacitor (energy storage) and the tunnel diode oscillator to complete the circuit. Thus, the energy harvested is used to send a UHF broadcast in the 412.2-412.3 MHz band, as seen in Figure 7.7D.

#2 Drawer Chest

In the second example, we manufacture an interactive drawer made of computational wood. This example uses a rack-pinion mechanism (introduced earlier 7.3.1), embed-

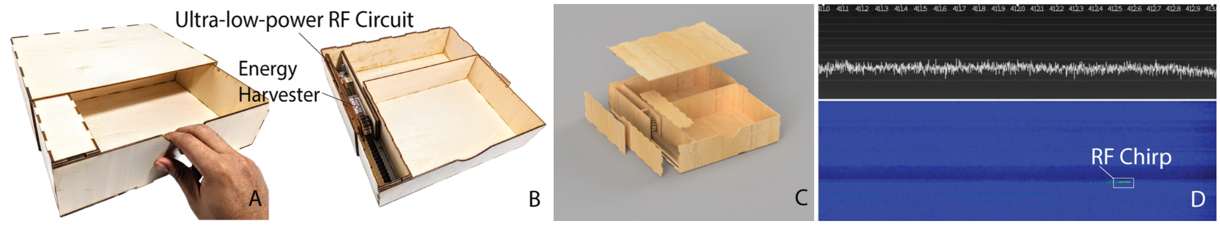


Figure 7.8: Shows interactive drawer, that harvests power from user pulling the drawer, to send a wireless interactive event

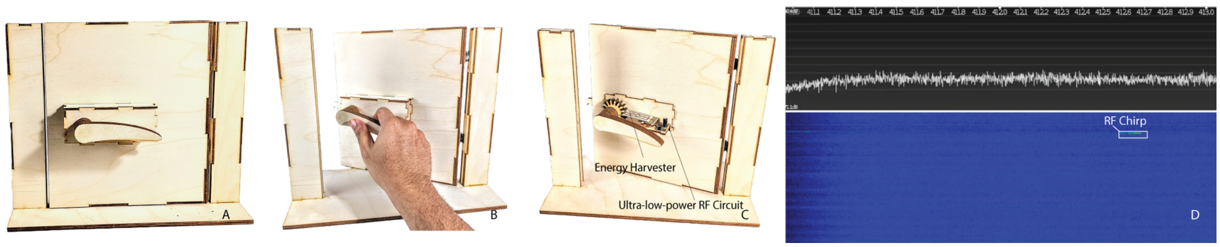


Figure 7.9: Shows interactions with a door handle, that harvests power from users mechanical action to send a wireless interactive event

ded within the drawer in plies of cross-laminated wood. When a user pulls the drawer from the chest, the rack that is attached to the drawer is pulled along. As a result, the gear attached to the rack rotates along to hit the piezoelectric material to generate power, which is rectified and stored in the capacitor of the RF circuit. When the drawer is fully pulled and has reached the final position (Figure 7.8A), the conductive trace of the capacitor (energy storage) is mechanically connected to the conductive trace of the oscillator circuit. Thus, the energy harvested is utilized to send a UHF broadcast in the 412.5-412.6 MHz band, as seen in Figure 7.8D.

#3 Door with Knob

In the third and final example, we manufacture an interactive door with a door handle that extracts power from the user's mechanical action. As seen in Figure 7.9 B, the gear attached to the handle rotates and hits the piezoelectric material embedded within the handle when the user presses the handle down. Once enough energy is harvested, it is released in the handle's final position (down and up), thus powering the embedded RF circuit to send a broadcast. As seen in Figure 7.9 D, the broadcast is received in the 412.6-412.7 MHz band.

7.6 Evaluation

In this section, we evaluate the computational wood's various subsystems (Energy Harvesters, oscillators, etc.) and how well they perform operating in the built environment settings. In particular, we go over three analyses, first, characterization of the power

Figure 7.10: Shows example objects: drawer, door handle, and input control device made of computational wood with envisioned embedded energy generation mechanisms

generated for interaction, bandwidth, & concurrent signal capabilities of our oscillator design, and finally, a sensing distance evaluation to understand the range at which we can operate.

7.6.1 Characterization of Energy Output

Computational wood offers many modes of generating energy, such as bending the wood, twisting embedded internal gears and mechanisms, etc. Here, we characterize the energy generated per corresponding interaction and the power needed to send an interactive wireless event.

- **Bending:** For every 5-degree bend in cross-laminated wood, we generate 79 mV. As we continue to flex, back and forth every 5 degree, the voltage across the storage capacitor increases. We tested our output in a six-layer ply of cross-laminated wood.
- **Gear:** As per our gear mechanism design, we generate 100 mV per gear hit. It takes nearly 6 hits to achieve the power needed to send a wireless interactive event. According to our experiments, this translates into 650 mV - 750 mV being generated for half a revolution (180 degrees) of the knob pictured in Figure 7.7 C, which is enough to power our oscillator.
- **Rack & Pinion:** The Rack & Pinion mechanism we designed produces 680 mV per 5cm movement of the rack.

We sought to understand the energy budget required to operate all the above modes of power generation. For each of the above modes, we recorded the rectified output from the capacitor using an oscilloscope, and then using the differential current measurement technique with a known resistor and load (RF circuit), we measured the current. Our experiments indicate that, on average, the various mechanisms of power generation yielded 400 microwatts of power, which is above the threshold needed (see Section 7.4.1) to generate a UHF broadcast.

7.6.2 Bandwidth & Concurrent Signals

Each device must operate at a unique frequency to support the simultaneous detection of interactions with many objects in wood. Therefore, the bandwidth required per computational wood device determines the total number of devices our system can support. As seen in Figure 7.9 D, Figure 7.7 D and Figure 7.8 D, our devices occupy / require a bandwidth of 0.1 MHz for operating without interfering with the sidebands while communicating. Now, if we look at the bands in which we operate 395-400 MHz and 410-450 MHz, that allows us 45 MHz of spectrum space, and hence the total number of devices we can support is 450 (i.e., 45MHz/0.1 MHz bandwidth). Although this is a theoretical estimate, we have noticed that environmental factors, such as temperature and moisture, can affect LC values, reducing the Q factor and needing more bandwidth.

7.6.3 Sensing Distance Evaluation

We have deployed our computational wood devices at various locations in an apartment, building, and neighborhood setting to understand the range at which we can operate our devices. These locations varied in construction types had many preexisting objects and electronic devices (such as refrigerators, microwaves, etc.), and offered varied room functionalities.

We first deploy an RTL-SDR receiver with a telescopic dipole antenna (2x 23cm to 1 m) that is highly sensitive to receiving signals at the entrance of a residential apartment (as seen in Figure 7.11 A, with an antenna symbol). Then an experimenter manually turned on the transmission of the computational wood device at different locations in the apartment. For example, see Figure 7.11 A, and the red dots represent the transmission locations. These RF transmissions were captured by the receiver and recorded by the SDR device located near the entrance. Reception was maintained to the furthest available location, the apartment's balcony, which is 41 feet 8 inches from the entrance beyond three walls.

We also recorded transmission from areas outside the residential building to test our sensing range as an additional evaluation. As seen in Figure 7.11 B, we were able to receive signals from two locations outside the building accurately. First, from a parking lot adjacent to the apartment complex, 150 feet away from the receiver, another parking lot of a high school (250 feet away) is opposite the apartment complex.

Figure 7.11: (a) Shows floor plan of house tested, transmission locations tested are represented by red dots (b) Shows testing range outside a residential building in two parking lots located 150 feet and 250 feet away

7.7 Summary

With computational wood, we introduced new capabilities to engineer wood, sustainable material with battery-free wireless sensing capabilities. We described various methods in which piezoelectric energy harvesting materials and mechanisms are embedded in wood such that power is generated by mechanical action from users. We introduced an ultra-low power RF circuitry (120uW biasing power) to create UHF wireless broadcasts in wood. We contribute a range of interactive wooden objects such as door handles, input devices, and drawers that utilize our methods for energy harvesting and enable wireless operation without batteries. We then investigated the power budget, bandwidth allocation, and range at which we can operate our computational wood devices in built-environment settings. Our vision and hope with computational wood are to offer designers and engineers novel ways to sustainably digitize our built environments into battery-free interactive surfaces and devices.

Chapter 8

Navtiles

8.1 Introduction

In the previous chapters we looked at approaches to make built environment form factors embedded with interactivity using computational infrastructure materials framework (formfactors, sensing & power, actuation, wireless communication, digital fabrication). While there are many interesting applications that are enabled by the technology-first approach, we were motivated by solving high impact specific application of the approach in real-world setting, i.e., in supporting accessibility of nonvisual navigators. In this chapter, we present a project which uncovers insights from the field about how to practically deploy computational infrastructure materials to support application domain-like accessibility through multimodal tactile guidance surfaces.

Mobility has transformed over the years with the availability of navigational technologies. Many of these innovations help with nonvisual navigation assistance. These tools collect information through computer vision, GPS, robotics, crowd work, and more to provide cues in a variety of mediums, from audio to haptics. However, studies [252] have shown that tactile features of the built environment remain an important, versatile, and underutilized perceptual cue. Orientation and mobility instructors train non-visual navigators to utilize many tactile cues from indoor and outdoor environments [103]. Well established techniques such as shorelining, trailing the wall, and more, enable students to recognize cues from walls, the grassline on the pavement, and railings with great success. Furthermore, navigators can leverage cues from objects such as fences, mailboxes, traffic signs, fire hydrants, or benches while also detecting changes in terrain.

While many such natural tactile cues exist in the built environment and are used by non-visual navigators, these cues are often not reliable as they can be discrete (not continuous) and available only for short durations while navigating. As a result, the built environment is outfitted with purposefully installed *tactile guiding surfaces* that exist in various tactile patterns to support non-visual navigators with warnings, alerts, and guidance. Tactile guiding surfaces in the built environment, however, have held a contentious place in the process of supporting navigation by people who are blind or visually impaired. Despite the relatively small set of individual textures, the standards for tactile guiding surfaces are vague and the implementation of pavement is not consistent [226]. This often leads to confusing situations for non-visual navigators, and in extreme cases, even injuries. Also, the information conveyed through tactile guidance surfaces is prone to cross-talk with other environmental noise such as foot traffic and has detectability issues due to weather conditions like snow or mud [117, 174]. Finally, most prominently, they do not help with geographic orientation during wayfinding, i.e, the tactile guidance surfaces inherently lack the ability to determine position relative to the final destination, topography, or distance in an unfamiliar area [41]. While such gaps exist when using tactile guidance surfaces, these gaps could be potentially alleviated by further exploration in design and augmenting the existing tactile guidance surfaces with additional modalities such as audio or vibrations [198].

In this chapter, we then describe our mixed-methods investigation with a survey of 67 blind or visually impaired travelers as well as interviews with 10 orientation & mobility (O&M) instructors and public accessibility experts. We share results about the role of tactile cues in everyday non-visual navigation and attitudes surrounding the use of guiding surfaces. Our participants revealed several opportunities for augmenting existing tactile surfaces with novel multimodal feedback solutions in immediately relevant contexts. We discuss insights from experts on practical aspects of implementation and critical issues extending beyond new design alternatives such as standardization, installation, movability, discoverability, and a need for transparency.

Finally, we offer a potential approach for rapidly creating low-cost multi-modal tactile surfaces with easily available materials and tools & techniques to widen the process of production. We highlight opportunities for augmenting tactile surfaces using available low-cost sensors and to amplify tactile feedback with audio. Taken together, our insights from key stakeholders – blind and visually impaired users, O&M instructors, and public accessibility experts – contribute to an understanding of how novel multi-modal navigational aids may be better designed and integrated into the built environment.

Survey Procedure

The survey was administered through Qualtrics and was available for three weeks. The survey link was shared through Twitter and in two closed Facebook Groups for people with disabilities. We collected over 100 responses. We removed responses with erroneous data (e.g. copy-paste answers, incomprehensible text) and excessively incomplete responses (blank sections, multiple skipped questions, etc.). This resulted in 67 completed responses.

The survey consisted of five sections and took 30 minutes to complete. The five sections are listed below:

- Demographics

Figure 8.1: (A) Shows two guidance surfaces intersecting without warning in (Taipei, Taiwan) (B) shows a guidance surface leading to stairs without warning in (Beijing, China) (C) shows Incorrect positioning at the entrance to a crosswalk (Paris, France), all example images referenced from [152]

- Navigation Background -inquiring Tools and Cues used for navigation
- Knowledge of Common textured Surfaces installed to assist nonvisual Navigation.
- Descriptive and qualitative experiences encountering Surfaces in different Contexts.
- Brainstorming new types of textured surfaces and accompanying multimodal feedback.

Survey Participants

We summarize responses from the first two sections here to introduce the background of survey respondents. We describe the remaining survey findings in Section 4. We received 67 responses to the survey. Of the respondents, 41 identified as female, 24 as male, and 1 person as transgender/agender. The majority of participants were blind (55%) as opposed to visually impaired or low-vision (41%). The remaining respondents did not specify their vision impairment. The majority of participants had their vision impairment since birth (65%) while 25% had their impairment for more than five years. The majority of survey respondents (43, 64%) reported primarily navigating in urban environments, while 13 (19%) and 6 (9%) indicated primarily navigating in suburban and rural environments, respectively. The majority of survey participants (52, 78%) engage in unfamiliar navigation either once or a few times per month, while 13 (19%) participants reported unfamiliar navigation once or a few times per week. Only two participants indicated daily unfamiliar navigation.

We asked participants to indicate their current use of and preferences for common tools and cues supporting navigation from a set of 14 options. The most used navigation tools were a white cane, smartphones, GPS, audio cues, human assistance, and tactile cues. The least used tools, indicated by a majority of responses having never used them, including guide dogs, wearables, and visual cues (asked for people with some useable vision). The frequency of use of vibration cues from the environment, like haptic feedback emitted by some accessible pedestrian signals (APS), was more evenly distributed across "never", "monthly", and "weekly" categories. When asked what tools participants would prefer to use if they had unlimited access, participants indicated the most preferred tools were the white cane, smartphone, audio cues, and tactile cues.

8.1.1 Interviews with Public Access and Mobility Experts

To complement our survey findings, we interviewed five O&M instructors and five public accessibility experts. According to the information service VisionAware[1], O&M refers to the instruction of safe, efficient, and effective travel techniques to people with vision impairments. As such, we recruited O&M instructors for their expertise in teaching non-visual navigation to help us situate our survey participants' experiences and suggestions in best practices and safety precautions. The public accessibility experts were recruited as we recognize that public implementation would require collaborative efforts of many stakeholder groups along with developing an in-depth knowledge of the ecosystems into which we would implement novel textured surfaces.

Interview Participants

We recruited five O&M instructors, four of whom were blind themselves. The fifth (O3) was sighted and had 33 years of experience teaching deaf-blind people, a population that may uniquely benefit from tactile feedback. The remaining four instructors all had experience teaching deaf-blind students and students with other disabilities in addition to blindness, though most of their comments considered nonvisual navigation that assumed normed hearing, spatial, proprioceptive (interpreting bodily movements and position in space), and cognitive abilities.

We recruited five public accessibility experts, two of whom were blind (T1, T5), one had a low vision (T3), and the last two were sighted, one of whom (T2) had physical disabilities and chronic illnesses. We note that O3's advocacy experience meant his expertise overlapped. They brought a diversity of experiences exploring, informing, and implementing accessibility features in public places. This expertise included enthusiastic and intentional travel to non-visually explore new public space (T1, T3, T5), experience working at public transit agencies to evaluate, implement, and train people to use accessibility features of public transit systems (T1, T5), consulting for government and corporate-funded public place and transit hub redesigns (T3, T4, O3), experience advocating governments for more accessible public places (T1, T2, T3, T5, O3), and experience reviewing crosswalk redesign plans for ADA compliance for a municipality (T4).

[1] https://visionaware.org/

Interview Procedure and Analysis

Each interview was conducted via phone or video call and took approximately 1 hour. Interviews with O&M instructors comprised an overview of their job responsibilities, what they teach their students about tactile feedback and an ideation session about potential use cases for new or more consistently implemented existing textured surfaces. Interview questions to public accessibility experts inquired a description of their relevant employment and advocacy, experiences with textured surfaces, and an ideation session about new textured surfaces. All interviews were recorded, transcribed, and thematically analyzed according to the interview questions [43].

8.2 Encountering Textured Surfaces in the Wild

In this section, we discuss findings from both the survey and expert interviews regarding the current role of textures and attitudes toward their use in non-visual navigation.

8.2.1 Knowledge of Available Textured Surfaces

We asked survey participants to indicate how they detected textured surfaces during navigation. Participants perceived textured surfaces through varying combinations of their hands (66%), feet (88%), and white cane (87%). Over half (51%) of survey respondents indicated using all three.

Through the survey, we also asked participants to indicate whether they had encountered and recognized common, purposefully-installed textured surfaces. The tactile pattern in surfaces applied depends on the context of its use, for instance, there are patterns that are more applicable in underground metros more than in sidewalks.

In our work presented here we asked participants about four different textured surfaces (see Fig 2) used in the US:

- Blister: Rows of round raised bumps, with flat tops and which are arranged in a square.
- Offset Blister: Rows of round raised bumps, arranged where each row is offset from the next.
- Along Stripes/Cycleway: Flat-topped bars run parallel to the direction of pedestrian traffic.
- Hazard: Flat top bars which are perpendicular to the direction of pedestrian traffic.

The variations in these patterns are both geometrical and based on the arrangement of textures in spaces. For instance, a hazard surface is a series of parallel rectangular bars placed perpendicular to the walking direction where the Guidance strips consist of rectangular bars parallel to the walking direction.

Surface Texture Pattern	Never/Less than Monthly	Multiple or once per month	Multiple or once per week	Multiple or once per day	Understood Texture Meaning
Blister	14	23	13	17	36
Offset Blister	45	9	9	3	8
Along Stripes/Cycleway	58	3	6	0	8
Hazard	56	5	4	1	2

Table 8.1: Frequency of encounters with common surface textures.

A summary of responses (n=67) for the frequency of encounters for each variation of tactile surfaces is given in Table 1. The table also summarizes the understanding of each surface. We asked participants to describe the type of information texture patterns were meant to convey. We counted responses that match the purpose outlined by the ISO standard for tactile surface indicators as understanding the meaning of the surface.

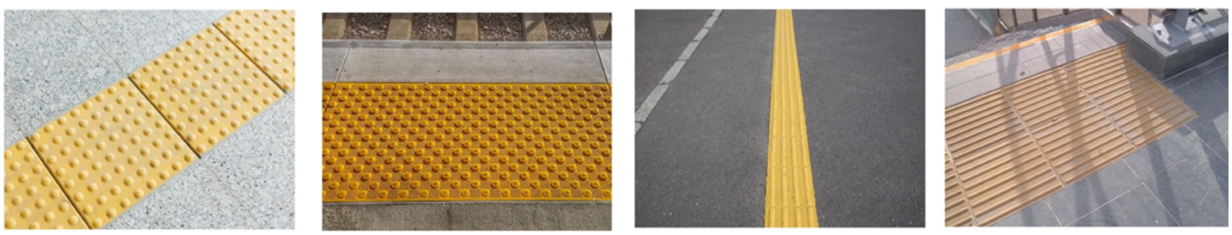


Figure 8.2: Shows most commonly used tactile guidance surfaces for non visual navigation

8.2.2 Using Tactile Features During Non-Visual Navigation

Participants suggested that visually impaired people extracted tactile cues out of almost anything. Many of the textures people use for non-navigation were not specifically installed for that purpose. This appropriation of available resources has been previously recognized in nonvisual navigation accessibility literature [74, 75, 141, 227, 251].

Encountering natural guiding elements has also been studied by urban theorists such as Lynch [143] in the seminal work of image of the city. They have classified elements into (1) discrete with examples like a tree, bench, signposts etc., and (2) continuous with a fence, channel drain, hedges, etc. It can also be understood that discrete landmarks are only available from time to time and they can be either tangible or intangible (like the smell of a bakery, air current in a block, etc). Furthermore, these natural guidings can be understood as either 1) fixed elements 2) semi-fixed elements or 3) non-fixed elements as the built environment continuously changes [190].

As these natural environmental elements are important for nonvisual navigators, it would be necessary to tackle the environment to be more communicative. Particularly towards making intangible landmarks more tangible and ensuring consistency due to non-fixed perceptual cues from the environment. Finally, where effective natural environmental cues are not available, designed solutions maybe implemented to avoid gaps along a guided route.

Across the board, our survey respondents (P#s), and all 7 blind interviewees hailed the importance of tactile feedback to nonvisual navigation. O1 pointed out that detecting tactile feedback is a primary purpose for using a white cane which, while in use, maintains consistent contact with the ground and nearby physical features. This provides a continuous type of tactile perception enabling key components of navigation including alerts, alignment, orientation, and confirmation.

> "When you have enough experience with the cane, and enough training, you can tell the difference between a poured concrete sidewalk versus an asphalt tarred street. So you can tell those texture changes. Usually, most tactile cues can be used to a traveler's advantage as far as if I'm walking in a shopping mall and I enter into a store, the hallway of that mall may have been tiled surface. When I walk into that store, I might notice a change to a wood floor or a carpet floor. When I'm walking down the sidewalk and I approach a corner, there's going to be some sort of a texture change. Those texture changes aren't universal but there is a texture change to be found and it's good to know you're at the corner, you don't want to walk into the street." - O1

Alignment, Orientation, and Confirmation

These textures also helped our participants align themselves in different areas like the library with sidewalks, parking lots, and random seating areas. The presence of both natural and purposefully built textured surfaces coalesce to provide feedback as to the orientation of the traveler and confirmation that they are in the right place or on the right path.

For instance, P65 states that they use "the cracks in the sidewalks to confirm I was on a sidewalk and not walking in a parking lot. I also used the grass line to confirm I was traveling in a straight path to my destination." Furthermore, P28 described using the grass and sidewalk edges to help maintain their position on a path.

P43 described using natural features to both confirm their path using known landmarks as well as to identify important temporary changes. "... a planter, or bench or metal trash can become something that is looked for to know that you are traveling correctly. Also, finding a cone with a cane makes you attentive that you might find construction."

The tactile features of street crossings provide useful cues for aligning and orienting a person to the correct direction of travel. O3 teaches deaf-blind students to line up in preparation to cross a street by triangulating textures both implemented for the purposes of assisting blind people and not. For example, he pointed out that their hand placed on a properly-installed accessible pedestrian signal pole can give a general direction of travel. At the same time, they can align their feet up so they are parallel with the line separating the sidewalk from a wheelchair ramp's descension and perpendicular to the curb. This alignment, O3 explained, starts the deaf-blind person walking straight across.

T5 mentioned that many street corners she encounters are not 90-degree angles, making textured surfaces particularly useful. b

> "[city] streets are weird. They sometimes come together at strange angles, like a 5-year-old drew a city....I think the arrows [on APS]...can be helpful." -T5

T3 noted that tactile pathways, apart from providing alerts and alignment, can help reduce circumnavigation, increasing efficiency toward reaching high-traffic destinations, which require traversing large open spaces. These examples taken together indicate that the alignment and orientation of tactual features play a crucial role in the navigational abilities of our participants.

8.2.3 Cautious Use of Surface Textures for Navigation

Overall, survey respondents and interviewees while indicating many potential benefits of tactile pavings also discussed the need for a level of caution when using. This was especially apparent for instructors and public access experts.

Don't Trust the Texture Alone

Interview participants (O's & T's) were cautious about trusting textured surfaces and suggested triangulating them with other cues. This caution was so pronounced that all five O&M instructors explicitly taught their students to not trust them. To these instructors, textured surfaces could provide alerts, quick confirmations of correct travel, or caution of incorrect travel choices. O5 collectively referred to these elements as "something different". However, the textures themselves do not provide detailed or holistic information. In other words, O5's, and all of the O&M instructors' students were encouraged to use other clues to determine what the "something different" actually was.

O5 explained a common scenario she encountered during lessons, "I've noticed them at parking lots and I've noticed students pick up those [textured surfaces] and think they're at a street and they count that as a street. It's not consistent enough." T5 corroborated the mixed messages textured surfaces could send.

> "We have a bus station in [city] that has all these truncated domes everywhere and I think it's supposed to show it's the edge of the curb don't go off the curb but if you'd don't know, is it to show this is a place to cross? There can be some ambiguity." -T5

This ambiguity also emerged from a portion of survey participants (n=11) who agreed that tactile cues were either misplaced or inconsistent. For example,

> "Recently, I shorelined along an unfamiliar street. Much to my surprise, there was a random tactile mat in the middle of the block. It served no particular purpose and didn't denote anything specific. Yes, there was a corresponding tactile mat on the opposite side of the street; in the middle of the block." - P27

To combat these inconsistencies, O1, for example, taught students to get a feel for how long blocks are, or the distance of a useful chunk breaking up their route, and be mindful of how long it takes. "If the distance versus time ratio isn't making sense to them, they might be at a parking lot entrance rather than the next street corner or other important landmark."

Inconsistent or Incorrect Installation Leads to Errors

Inconsistent and incorrect installation of textured surfaces, at worst, could lead people to cross intersections into moving traffic. Several interviewees (N=5) pointed out that whether or not textured surfaces are meant to provide alignment assistance, many blind people interpret a bumpy textured surface as an indication of a safe place to cross. However, many textured surfaces are placed inside wheelchair ramps that do not line up with the crosswalk or worst, point a diagonal trajectory across the intersection. Further, two interviewees (O5 and T5) had encountered specific instances where they noticed the tactile arrows on APS poles were pointing in the wrong direction. T3 and O3 explained these inconsistencies were so pervasive and general street crossing support so poor that many deaf-blind people only travel routes vetted by an O&M instructor. "Every route that a person learns has to be vetted for successful or ineffective installation. Maybe when there's an ineffective installation that person is not able to use that crossing." But inconsistent and improper installation could impact more than blind and deaf-blind people. T4, who reviews engineering plans for crosswalk redesigns and evaluates related ADA violations explained that such hazards may also endanger everyone.

> "There are a few larger buildings that installed these [textured surfaces] improperly. They actually had this little lip that could come up half an inch. People were tripping over them. They were coming up off of the sidewalks." -T4

We note this difference in caution between our survey and interview respondents. While an interview offers more time for longer answers, we also learn from their expertise; people may make incorrect assumptions about the utility of textured surfaces, or they may be installed incorrectly. Such errors could lead to danger, and thus keeping safety at the forefront of our work is even more important.

8.3 Priorities for Multimodal Feedback through Guiding Surfaces

We asked participants to discuss ideal new textured surfaces in terms of what properties they would have, what information they would convey, and in what situations or contexts they would be most helpful. We discuss these results as they relate to materials, feedback types, and contexts of implementing new textures.

Participants outlined several opportunities to provide multimodal feedback in addition to improving the tactile feedback options. The majority of these solutions combine the use of additional smart devices with audio and haptic feedback to obtain more information about the environment. We present findings regarding each, as well as suggestions for additional tactile feedback.

8.3.1 Desire for Mixed Materials

Descriptions of specific properties of textured surfaces' materials were mentioned in several survey responses (N=8). The material focus was mainly a juxtaposition between hard vs. soft surfaces, with participants either expressing preferences towards one type of surface or utilizing both types of surfaces to aid in surface differentiation. For example,

> "Perhaps something slightly squishy, like foam, versus hard textures, that could signal where doorways into buildings are, or important paths off shooting from a main thoroughfare." -P65

Over half of the responses that specifically mentioned materials envisioned surfaces with soft textures (e.g. rubber, foam). One participant, P66, specifically described their rationale behind their choice being that potentially softer surfaces that denote the presence of "any type of water surface (e.g. pool, lake, river, ocean, fountain) would help to prevent falls, injuries, and potential drownings". P27 emphasized the need for environmentally friendly materials, specifying how "upcycling would be ideal and low maintenance helps keep things cost-effective."

8.3.2 Audio Feedback

We categorized audio feedback into two types: sound feedback and voice feedback. Ten responses mainly focused on sound as a feedback mechanism either embedded into the textured surface or the navigation tool. For instance, P19 envisioned "a surface which made a particular sound when tapped with a white cane or made a distinct sound from the normal impact of feet on sidewalks or surrounding surfaces", while P3 described incorporating audio into the white cane to indicate other travelers or hazards.

Twelve responses focused primarily on potential voice prompts either embedded as a response to encountering the textured surfaces directly, entering environments with textured surfaces (e.g. an area surrounding the surface, such as streets and intersections), or to support proper and safe directionality.

The two categories of audio feedback ultimately converged on an overlapping topic of safety; that is, nine participants described scenarios where audio feedback can help them, for example, become more aware of other pedestrians, when to cross the street, and how to reach the other side.

8.3.3 Haptic Feedback

Similar to audio, the use of haptics was described in terms of use with a smartphone and the textured surface itself. The broader application of haptics to the Deaf and hard of hearing community was also mentioned. Participants (N=8) discussed haptic feedback (mainly vibration) as a feedback mechanism in response to the use of a tool such as a white cane to support crossing the street (P64). P6 described the use of haptics for encounters with textured surfaces, and the identification of specific landmarks.

> "Ideally, haptic feedback could be integrated, so perhaps the bumps could vibrate when it detected an approaching phone utilizing a travel app that was meant to likewise detect the warning bumps, or only the phone could vibrate in response." -P6

Four responses expressed a preference for haptic feedback due to concerns for the hard of hearing and Deaf community.

> "I think by adding a vibrating alert it would be another layer of protection…I have met many other people like myself who are not only blind but also hearing impaired. Therefore, I feel the vibrating stimulation would be more impactful than one that is auditory." -P66

8.3.4 Visual Appearance and Aesthetics

Another aspect for consideration was aesthetics and how it affected social attitudes. T3, who has experience consulting corporate as well as government-funded projects, noted the importance of satisfying access needs while maintaining the desired look and feel, an intersection she believed actually fostered more creativity. Throughout her advocacy, T2 has seen this in practice; she has used a municipality's choice to renovate their downtown sidewalks to maintain dark red brick while ensuring high-contrast bright white brick was used to denote street corners. In this case, providing a warning of street corners did not come at the expense of preserving history.

Many tactile guiding surfaces are already "multimodal" as they are often designed with high-contrast colors to support low-vision navigation. T3 explained the many factors that must be considered when designing the visual appearance of textured surfaces both to make them more aesthetically pleasing as well as low vision accessible, especially in outdoor conditions.

Beyond the specific types of feedback, the visual presentation of textured surfaces could have an effect on how passersby code the purpose of the textured surfaces and blind people. T3 noted that it was important for her blind stakeholders that they are not perceived as walking on the 'blind path.' Though none of our interviewees experienced this directly, they shared stories of their students and blind friends experiencing public humiliation by passersby if they were not walking on textured guide paths. Whereas passersby may have thought they were being helpful to point out the existence of a guide path, O2 and T5 mentioned this assistance became patronizing if a blind person did not prefer to use it or was going somewhere different from where the path led.

Relatedly, O4 experienced frequent patronizing and sometimes misgendering assistance while reading braille signs. Passersby would suggest that whichever bathroom sign they were reading, for example, was either the right or wrong place where they should use the restroom, raising important awareness about the deeply personal nature of, and the longstanding discriminatory histories such assistance may involuntarily bring a user's attention to. T3 believed that if textured surfaces are ultimately meant to be interacted with up close, thus probably engendering unwanted attention, textured surfaces that took on the aesthetic of the environment and provide utility for more than blind people may help to destigmatize sticking to, or not sticking to, a particular path.

While we acknowledge the insufficiency of secondhand accounts, this reminder hints at specific considerations when designing and evaluating textured surfaces to, as researchers have advocated for years, consider their effect on passersby and their social accessibility.

8.3.5 Optimize Feedback to Reduce Cognitive Demand

With the promise of multimodal feedback, there also comes the concern of too much information. Interviewees were enthusiastic about textured surfaces outfitted with haptic and audio feedback but noted that it must be implemented thoughtfully. Five participants expressed concerns about distractions that may arise from navigators needing to pay attention to too many signals. O5 listed several potential sources of information a student may be triangulating, and cautioned these sources could be many, underscoring the need for information sources to be voluntarily activatable if not sharing the more pertinent information.

> "The con is you have something talking to you plus you're listening to traffic plus you're trying to feel truncated domes plus you're trying to feel an arrow. Some students, in particular, can get really distracted by all of that information." – O5

There was concern that stepping on a vibrating surface, for example, would alarm some people; and even if activatable, if others could be standing on it and unaware, they could still be alarmed. Whereas expecting people in public to traverse textured surfaces seemed reasonable, interviewees cautioned that other types of feedback should be voluntarily activated, and haptic feedback may be best transmitted through poles (O3).

8.3.6 Placement of Future Textures in Public Spaces

All participants were generally positive about the idea of new textured surfaces to support nonvisual navigation. While survey participants generally provided speculative future uses of novel surface textures, interviewees first wanted existing textured surfaces that are known to be helpful to be installed in more places. For example, several noted (N=37) that textured surfaces might be installed near crosswalks of busier streets and in newly renovated or constructed areas, but much of the built environment lacks them. They suggested that amplifying existing textured surfaces that are known to be useful is an important first step to supporting tactile feedback during nonvisual navigation.

Public transit stations

Seven survey participants specified the need for more effective organization of tactile cues related to transportation, either regarding approaching transportation stops or traveling within large transportation hubs (e.g., train stations, airports). All seven blind interviewees reported that bus stops are almost always difficult to find given their inconsistent features and how difficult transit stations are to traverse. T1, who gained extensive knowledge about his city's public transit by working at the agency and teaching people to use it described a time when he waited in the wrong place since the bus stop was not tactually different. "I sat there and I heard the bus come by. Well, it passed by. Come to find out, I was standing at a speed limit sign. [T1]" T1 and others shared that even experienced travelers still encounter difficulties finding where to board public transit and noted it a fruitful place to innovate on textured services since there may not be sufficient environmental clues to take advantage of. P54 suggested

> "I'm picturing a textured surface with ridges, made of metal or plastic, that could be easily detected with a cane but would be flush with the surface of the sidewalk. I could see these being very helpful at the transit center, where I need to find the exact place where each bus would stop. As I'm walking along, these exact bus stops are not easy to find, since I can't see them. These would be very useful for marking bus stops anywhere in the community. If a change is made in where the bus stops, they could easily be removed, and asphalt squares could be installed in their place." -P54

This story is reminiscent of many others [46, 227], but many interviewees really wanted to tactually discern bus stops and preferred to learn only more complex information through smartphone apps, the solution proposed in this prior work. O3, for example, believed poles at textured surfaces marking where train doors would open would be excellent places to provide localized vibration and audio feedback for on-demand updates about next arrivals.

Mixed-use public places

Mixed-use public places are areas where people traverse near different types of mobility aids (pedestrian, biker, scooter, vehicle). Three interview participants explicitly noted new construction in their areas that contained no tactile boundaries between these spaces in the original design. While meant to ease movement and emphasize non-vehicle modes of transport by, for example, narrowing streets to make room for bike lanes, the proliferation of these tactually ambiguous mixed-use zones was concerning to interviewees. From O3's advocacy, he noted textured surfaces installed as an afterthought to provide some boundaries need to be particularly prominent as the consequences of missing them could put pedestrians in danger. However, if the texture too much resembles that at crosswalks which participants found quite detectable (like T5's prior-quoted concern), they could pose an additional danger by being interpreted as a safe place to cross. On one project, O3 noticed large planters replacing a textured surface determined not detectable enough by blind stakeholders. The blending of traffic in mixed-use movement zones provide an opportunity to re-emphasize early involvement so textured surfaces and appropriate barriers are robust and well incorporated into the landscape.

8.4 Practical considerations for Implementation

Interviewees and survey respondents shared important factors to consider during the design of textured surfaces which align with several features of good design. As textured surfaces tend to be found in the built environment, however, these suggestions not only concerned the surfaces themselves but the entire process of their design, installation, movability, and learnability. The latter three phases have been addressed more sparingly in accessibility research. To elucidate these suggestions, participants often shared their experiences encountering or collaborating on projects with various successes and failures.

As mentioned, inconsistency in the environment created frustration and mistrust in participants; any textured surface must have a consistent design and implementation. This suggestion was so prominent as highlighted by T5, adhering to it could transform the guesswork of interpretation, "Tactile feedback could play a much bigger role if it were to be used consistently. (T5)" For example, even if textured surfaces are designed according to best practices, they may still be installed incorrectly. This raises the need for fabricators to take on advocacy and scaffolding work to help ensure partners in augmenting the built environment do not morph what could provide useful feedback into yet another distraction.

8.4.1 Standardization

Throughout our study participants described issues with inconsistent and incorrect installation and use of purposefully installed textures for navigation. We reiterate the importance of standardization to address these issues while maintaining that the process for doing so may not be as straightforward as practical constraints and multiple stakeholders can make coordination difficult. Participants highlighted the significance of standardization regarding materials: "There needs to be national standards, that is, using the same system everywhere so they are uniform" (P52). Such standards do exist however their enforcement may be far less universal as P63 explains:

> "I don't believe that we blind and [visually impaired] need yet another tactile surface for navigation. Just like with legislators, we don't need more laws — we need laws standardized, funded, and enforced. I urge you to develop and implement a standardized set of tactile interfaces that are globally agreed to and applied. Funding, then, is directed toward production, implementation, servicing, training the trainers, and training individuals." – P63

8.4.2 Installation

Interviewees noted that installation must be done properly and consistently for users to benefit the most. At best, inconsistencies produced unwieldy searches like T1's experience at hotels, "If you go into any building the braille sign is never in the same place as another building. For instance, I can go to a hotel and the room number may be on the door or the left side of the door, or the right side of the door. So you never know. You have to feel around for it." At worst, however, as mentioned previously, incorrect installations could lead users into the middle of intersections or even become tripping hazards.

T3 spoke of another project that sounded good in theory, but insufficient feedback loops meant a test implementation went unverified, rendering the textures useless.

> "We said we need signs, and these signs need certain criteria and they need braille, raised print, and raised arrows but how do the people find the signs? We created this ground texture, and then we agreed on that ground texture with blindness stakeholder groups. But when they put the stuff down you couldn't feel them well so they did it, and then they didn't really have us back to check it in a timely way. So it was awful because I went and looked and felt, and this whole team was all feeling and we couldn't really feel the difference between the walkway and the indicator to tell folks where the sign was." -T3

As part of her consulting, T3 aims to get her clients to engage stakeholders in tight feedback loops, long advocated by accessibility research. Apart from their reminder to more deeply engage stakeholders, these shortcomings point to opportunities where accessibility researchers might incorporate these cautions and collaboration best practices during installation, not just prototyping.

8.4.3 Movability

O3 was our only interviewee who had extensive experience designing accessible pathways through an ever-changing landscape: a machine shop that employed several blind people. However, we believe his wisdom is useful for temporary contexts. For decades, the machine shop comprised pathways made of thermoplastic that had to be ground down whenever the shop design changed, and the pathways needed to be redrawn. This process became unwieldy as the shop floorplan changed frequently. They have since transitioned to using metal plating like that found covering underground access points along sidewalks. O3 mentioned the metal material would be inappropriate to use outdoors as they are a slipping hazard when wet, but for their indoor shop, it can be screwed into and unscrewed from the concrete flooring with available tools, is easy to procure, and provides sufficient tactile and audio feedback for deaf-blind and blind employees to travel efficiently. Whereas metal may be inappropriate in some indoor environments, the lesson to think of the possibilities textured surfaces may need to be moved if they are used for pop-up events like poster sessions at conferences, or if bus stops are redistributed, while choosing durable materials that do not move accidentally is important.

8.4.4 Discoverability and Learnability

Almost all interview participants appreciated the potential for textured surfaces but acknowledged that learnability is an ongoing challenge. This sentiment was echoed by survey participants who broadly expressed a desire to be more well versed in the meaning of existing textures and tactile features. Some, like O3, recommended locator tones like those used to denote the nearby presence of an APS; and O4, among others, recommended that tactile feedback could be outfitted with sensors that alerted smartphone users of their whereabouts to limit the environmental noise. T3 and T5 described how websites and audio announcements could be used to provide travelers with instructions for how to locate accessibility features like tactile maps and signs. Additionally, connections, or lack thereof, could impact discoverability, learnability, and ultimately, utility. O3 pointed out the consequences of helpful textured surfaces that fail to connect their users to a point where they can pick up other helpful cues when the textured surface ends. To exemplify this, he recounted a project gone wrong:

> "It's important that the [textured surface] intersects with the likely path. … The [textured surface] wasn't extended from the station out to the streetscape, so there was no wayfinding material to assist someone from the station through the plaza which has a bunch of street trees on the side of it in raised beds that working that plaza is difficult or impossible for someone who doesn't have experience already. ... They need to think about the connection between the [train] boarding and the streetscapes. People need to

> be able to get out of the station to get on their way." -O3

O3's anecdote demonstrates the importance of thinking about the before and after when designing textured surfaces; in what ways may the user be encountering them, and in what ways should the textured surfaces support them on their way? The misstep of not connecting a textured guide path along a train station's platform to a nearby street with well-defined sidewalks rendered the textured surfaces less discoverable, and therefore, less useful than they could have been.

The most consistent request from interviewees was for more tactile feedback to denote the presence of bus stops and to provide guidance in public transit stations. They noted discoverability in these scoped locations may be easier because of consistent station layouts in some cases or consistent features, like stairways and elevators, such that a common language could be established. If someone can find one landmark detectable by a cane, they may then know how to orient to additional feedback.

8.4.5 Need for Transparency in the Process

Finally, discussions with public transit experts revealed the importance of transparency in the process of producing and implementing textured surfaces for navigation. The four disabled accessibility experts (T1, T2, T3, T5) noted that processes for implementing textured surfaces and other accessibility features in public remained opaque. There continually is confusion about how citizen-reported ADA violations were determined to be actual violations or to be feasibly fixable or not (T2) and the reasons behind decisions that insufficiently outfit new projects with accessibility features (T1, T2, T3, T5). To these public accessibility experts, communication among stakeholder groups was insufficient. T5 echoed that these problems even existed inside of the transit agency where she worked.

> "When other departments in the system decide to make changes, they are supposed to consult us. A lot of times they did but there were always those times that stuff happened that we didn't know about which was very annoying and frustrating." -T5

T4 outlined the various stakeholders involved in implementing public accessibility features: an ADA coordinator, the engineer who reviews plans, funders, a project contractor, construction workers, and pedestrians. The ADA coordinator liaises with external stakeholders who may or may not be consulted for feedback proactively depending on whether the agency thinks the potential solutions are unclear.

T4 further admitted that though his municipality's interpretations of the ADA formed standards are publicly viewable online, many complicated design decisions and negotiations are often handled on phone calls. This leaves few traces about how such decisions are made for public critique, revision, or, in our case, design inspiration, manufacturing process, and tool development guidance.

8.5 Design Recommendations for Multimodal Feedback Enabled Navigation Tiles

We have thus far reported factors and situational contexts that textured surface designers and practitioners must consider from multiple perspectives that include blind people, O&M instructors, and public accessibility experts. In this section, we overview the design recommendations for key technologies from stakeholders' perspective to alleviate the challenges that non-visual navigators face when interacting with textured surfaces. We outline our proposed recommendations to enable the creation of low-cost, customizable, multi-modal textured surfaces. Our design recommendations are broadly situated over three areas: democratized production of tactile surfaces, multi-modal sensing, and feedback, and support for planning and installation.

8.5.1 Democratized Textured Surface Production

Open process for consistency

Due to the cost and complexity of the current production methods, there is a high barrier for further tactual exploration and physical validation of consistent standards in textured surfaces. To enable a wide variety of textures and to validate the consistency, a prototyping method should be open and accessible to teachers and other stakeholders. Current methods, unfortunately, do not afford such exploration, precision-engineered mold takes 2-3 weeks to be machined before it is used to mold a textured surface. By incorporating rapid prototyping technologies such as 3D printing for making molds, the time to prototype and explore newer textures is drastically reduced. Having a low-cost customizable production model also enables stakeholders to quickly understand what is feasible, which may enable tighter feedback loops to address issues with surface installation.

Support new materials & textures

Further, by having an open-source process, new material explorations are possible for many of the textures desired by our survey participants as illustrated in Section 4.2 and 5.1. For example, textured surfaces provided participants important information, but their presence and meaning weren't always discoverable. Different texture shapes were often too similar to draw participants' attention to their differing meanings. To be discoverable, textures should have a contrast with the surrounding environment such as hard guidance surfaces on otherwise soft surfaces & materials. Furthermore, research in advanced materials [84] has identified texture changing polymers that could be incorporated into surface production. While a lot of mixed material prototyping is possible and HCI research may recommend new designs, we should collaborate more with materials, civil, and other engineers to confirm that the safest, most durable, and feasible materials are being used.

8.5.2 Multimodal Feedback Sensing and Feedback

While current textured surfaces are often manufactured as singular modes of information (tactile), we learned, as well as others [227, 251] that many feedback sources are combined to inform navigation decisions. Further, textured surfaces were often misunderstood which could lead to incorrect or even dangerous navigation. In many of our interview and survey responses, participants alluded to either not recognizing the textures or detecting them and being led to the wrong location.

Participants perceived the benefits of multimodal feedback to complement textured surfaces that could assist in learnability and appropriate use. This is consistent with our survey participants supporting the idea of audio or haptic feedback with the preference to receive the audio through their personal devices and further control of activating such messaging. With low-cost conformal electronics material such as pressure-sensitive textiles, a system could detect user input before delivering audio feedback. Audio feedback could be provided as prompts or voice feedback, as desired. Further, audio feedback could be continuous (e.g. as turn-by-turn directions) or intermittent.

Support Multimodal Feedback Customizability.

However, we note that multimodal feedback should be customizable to prevent information overload. As participants also describe the need to minimize or control information flow to avoid information overload while navigating. NavTiles should allow users to customize when they receive feedback, control of the frequency, and duration of voice prompts should lie with the user. NavTiles should support users to receive information on their own devices than public infrastructure (such as poles, sidewalks, etc.) to avoid confusing nonusers.

Supporting learnability & discoverability.

While navtiles should be implemented at obvious stopping points (e.g. crossings, intersecting paths), multimodal feedback (audio+tactile) could be used to support the discoverability and learnability of new and existing textures by providing detailed information such as transit stop names, different paths, or pointers to other landmarks.

8.5.3 Consistent Installation, Deployment and Resource Planning

Support consistent standard implementation

Having an overview of where to implement tiles (in the built environment) helps resource planners and implementers might lead to a more consistent implementation outcome (see Section 4.3.2). Hence software for multimodal tiles should support an overview interface to track and plan tile locations. Finally, existing standards do not address multimodal feedback and are not followed consistently, as evidenced by participants encountering surfaces with inconsistent meanings. In the planning app, these standards could be designed, incorporated as templates and warnings can be implemented when a user deviates from the design. Finally, the toolkits & software used to prototype NavTiles could incorporate information about required approvals before installation. Future research should work in collaboration with materials, civil engineering, and policy experts to refine and distribute standards.

Support movability

Besides installation, another key area is to help support movability or constant environmental changes around where tiles are deployed. This means that when tiles are moved, their meanings may change; one way to accommodate that is by enabling implementers to keep track of which tile is deployed where and enable them to update audio instructions for the tile feedback or prompts. The potential portability and multimodal feedback of NavTiles may also be applicable in temporary setups, such as street fairs, where permanent infrastructure may be infeasible. For example, interviewees mentioned textured surface movability was imperative when workstations in a shop changed.

Support Diverse & Safer Involvement in Future Research

While the textured surfaces are typically implemented by governmental agencies, if there are delays or lapses in this installation, this open, low-cost process may enable a broader & diverse audience to deploy custom textured surfaces to fill gaps in the system. Partnership with blind people, especially deaf-blind people who may rely even more on tactile feedback, may help reduce the inconsistent textured surfaces that confused participants. Future research should also be cognizant of successful navigation techniques to complement, without overshadowing, other sensory information. Finally, we should use existing safe spaces as testbeds for innovation. Due to safety concerns related to testing material durability and confusion over textured surface meaning outlined by participants, prototype technologies must be deployed responsibly with clear boundaries first.

8.6 A Prototype Implementation

We conducted exploratory prototyping activities to develop a process for producing textured surfaces with embedded sensors, capable of providing multi-modal feedback to non-visual navigators. This consisted of three components: planning, fabrication of tiles, and embedding of interactive elements. All of the components presented for the NavTiles prototype system (web app, hardware, etc.) have been completed and tested for functionality. Future work will involve testing of the prototypes with blind people and initial deployments.

Planning Application: Users can plan where they want to instrument a navigation tile in the environment using a planning app, where custom layouts can be uploaded and tiles with different textures can be placed with corresponding audio prompts. On

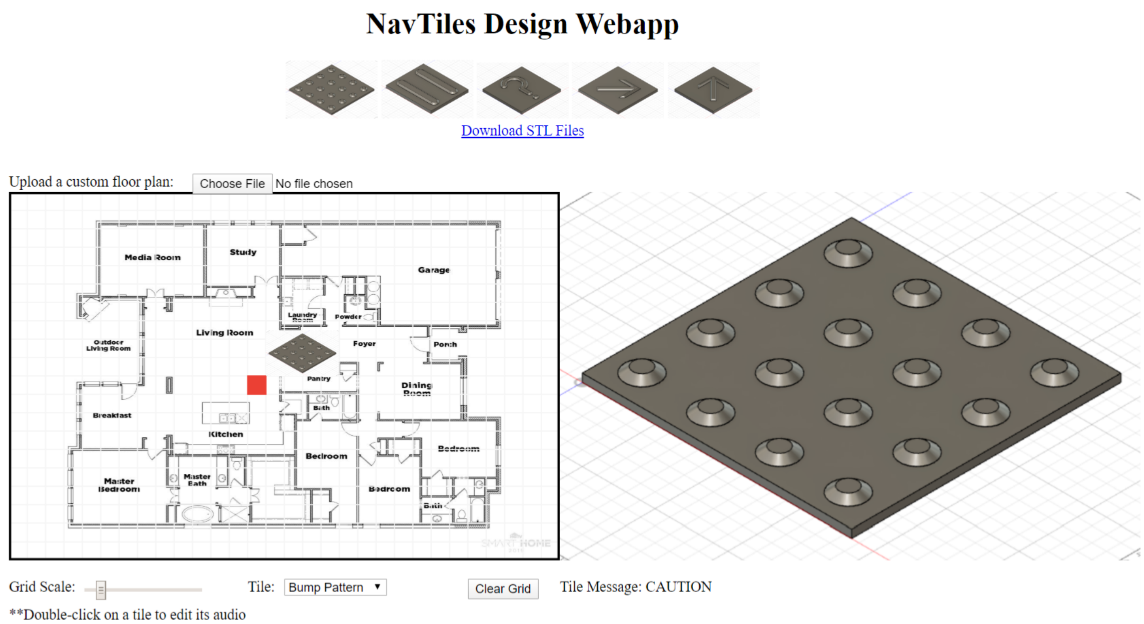


Figure 8.3: Shows a web application UI for custom planning of the tiles and recording audio prompts. This application is running on a web server and is sending audio prompts to users phone

deciding the type of tiles, users can download the necessary files to produce 3D textures. The planning app is shown illustrating an indoor installation in Fig 3.

Fabricating a NavTile: To make a textured surface, users can 3D print the texture elements using a wide variety of materials. Desktop 3D printers with low-cost thermoplastic materials are available as low as $99. While a one-off custom designed NavTiles could be 3D printed tile (as seen in Fig 4A) can be used as-is, the original could be used as molds for more replication. For instance, the printed objects can be used to make several copies using a low-cost DIY vacuum former (Figure 4A).

Integrating Sensing Assembled tiles can then be interfaced with textile pressure sensors (costing <$2 per m2) called VeloStat to detect a user's step. These pressure sensors are connected to an ESP32 IoT device which is run on a battery (see Fig 4C). The pressure sensors are simply attached to the back of the tiles, as a user steps on the tile, the change in resistance is detected by ESP32 to trigger the audio.

Networked Connection and audio In order to uniquely identify the user, we can receive a Bluetooth signal from the user's phone. As soon as the user interacts with the tile, a request is sent to the webserver from internet-connected ESP32 through the MQTT protocol and audio of pre-recorded message for the corresponding tile is played to the user's phone.

Figure 8.4: (A) Shows 3D printable textures and a thermoformer for making a texture, (B) Shows guidance surfaces inter-locked with each other (C) Underlying electronics, a sensor to make the tiles multi-modal.

8.7 Summary

In this chapter, we investigated the role of tactile cues through a mixed-methods study with blind travelers, O&M instructors, and public accessibility experts. Our study uncovered the role of tactility in everyday navigation and attitudes surrounding the use of tactile guidance surfaces for non-visual navigation. Our findings indicate that tactile cues although are very important and useful remain inconsistently applied in the built environment and potential breakdowns happen.

Further, our findings reveal several opportunities envisioned by participants for augmenting the existing tactile surfaces with multi-modality, i.e., not just tactile alone. The perception from each stakeholder group is of cautious optimism while being open to new advances in multi-modal textured surface designs. We further discuss implementation challenges expressed by our participants such as standardization, installation, movability, discoverability, and a need for transparency in any new design alternative.

Finally, we offer a potential approach for rapidly creating low-cost multi-modal textured surfaces with easily available materials and tools to widen the processes of production. We argue that new design alternatives alone are not enough to support nonvisual navigation but pragmatic implementation complemented with insights from key stakeholder, the context of use is needed for long term change.

Chapter 9

Conclusion

9.1 Thesis Contribution

In this thesis, we introduced computational infrastructure materials that enable low-power, integrated sensing, and actuation in the networked physical infrastructure forms (e.g., buildings).

The motivation behind developing computational infrastructure materials is that today's Internet of Things (IoT) is still not everyday "things" that we interact with in the built environment (e.g., furniture). To truly enable human interaction, affordance, and computing to be pervasive, we need to manufacture computational capabilities into 'things' (e.g., table, chair, etc.) with considerations of power, sensing, form factor, actuation, and communication [27].

To this end, in this thesis, Chapter 4 introduced a method for manufacturing computational capabilities in room-scale physical structures such as walls, tables, furniture, etc., using a power-efficient optical approach. Common infrastructure materials (concrete, plaster, etc.) are programmatically embedded with optical fibers to provide sensing and displays for interaction with structures. In Chapter 5, Fiberwire introduced a digital fabrication pipeline to turn an advanced structural material, such as a carbon-fiber composite, to transmit electrical signals at a low loss. Using FiberWire, users can 3D print mechanically strong, light-weight composite objects (e.g., bike handlebar) with inherent conformal circuits and printed sensors. In Chapter 6, we demonstrate a range of techniques and design primitives that support the interaction and actuation of large-scale pneumatic truss structures. These structures can self-deploy, predict user interaction, and respond by actuating various parts like doors, windows, etc. In Chapter 7, computational wood introduces a new wood fabrication method that enables wireless sensing and interaction without batteries. We engineer wood such that piezoelectric materials and ultra-low-power (120μW) RF circuits are embedded between the layers of wood. When objects such as dressers, door handles, input devices, etc., are manufactured with computational wood, human kinetic interaction (e.g., pulling the drawers) powers the underlying circuitry to send interactive wireless broadcasts. Finally, Chapter 8 introduces Navtiles, providing insights from the field on how novel multi-modal, computational infrastructure material aids may better support the accessibility of the built environment for nonvisual navigators.

Across all of this work, this thesis first enables a wide variety of interactive forms in the built environment, such as interactive walls, tables, drawers, doors, facades, sidewalk surfaces, etc. By expanding the range of materials with which form factors are built, i.e., infrastructure materials, this thesis contributes to devices with novel material capability. For example, building devices with extreme mechanical strength (Chapter 5, devices that operate on the scale of the built environment surface (Chapter 4, Chapter 6), devices made with natural sustainable materials (Chapter 7), etc.

Second, this thesis offers sensing approaches for seamless form and material integration. One of the main contributing goals is to remain sensitive to aesthetic considerations while providing robustness for harsh conditions of use (as seen in Chapter 4 and Chapter 5). The approaches introduced in this thesis achieve the goal of deeper form integration by modifying the properties of materials to transmit signals such as electrical, optical, vibration, ultrasound, etc. to support sensing. Finally, to support the scale of the built environment, the introduced sensing techniques also support longer range (operating at hundreds of feet) using zero local power (Chapter 4) or no batteries (Chapter 7).

Third, this thesis demonstrates larger-scale actuation capabilities with mechanisms embedded in the built environment form factors such as domes, facades, etc.

Fourth, this thesis contributes battery-free wireless communication capabilities in a sustainable built environment material such as wood (Chapter 7). This contribution endows built environment forms (such as doors, drawers, etc.) made in wood with innate wireless interactive capabilities.

Finally, this thesis offers a range of digital fabrication processes and machinery that enable end-users to work with built-environment materials such as concrete, plaster, composites, geotextiles, and wood. These fabrication processes also contribute towards democratization and end-user fabrication or modification of built environment forms with custom computational capabilities such as sensing, wireless communication, and actuation.

Together, all these contributions lead to a vision of how we may reimagine creating next-generation ubicomp devices that are power savvy, deployed on a larger scale, and more deeply integrated into our built environment.

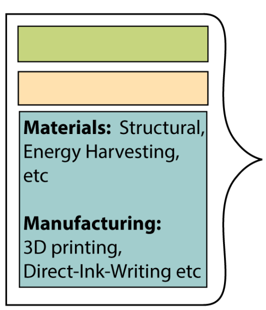
9.2 Future Work

There are many avenues for future work when developing interactive computational materials for the built environment. In this section, we discuss several steps to further push the agenda.

Figure 9.1: Shows approach to for building interactive computational materials combining – materials & manufacturing, computer architecture and AI & interactive capabilities and applying to various areas in the built environment. Future areas worth exploring are shown in a red dotted box

Although the current focus of this thesis has been on room-, building- and neighborhood-scale interventions in the built environment, future efforts could focus on efforts beyond, such as city-scale and metropolitan area scale. Specifically targeting opportunities in urban agriculture, landscape, parks, streets, etc., as highlighted in Figure 9.1. While targeting these avenues, advances in three areas are essential:

9.2.1 Materials and Manufacturing innovations for sustainable built environment devices



The current major bottleneck with IoT devices is power. Even if we assume a 10-year life span for a single IoT battery, we need to replace 270 million batteries every day in a trillion IoT device world [27].

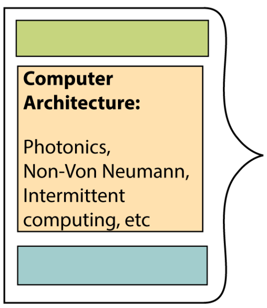
Therefore, innovations in energy harvesting, storage, and low-power communication materials with consideration to the built environment form factors are essential.

Energy Harvesting: There are many promising avenues for extracting energy from the built environment, this thesis explored the extraction of energy from mechanical stress (piezoelectric), beyond the thesis, we have begun to explore avenues such as light (photovoltaic) [268]. In the future, we could explore other approaches, such as friction (triboelectric), pyroelectric, and urban wind energy harvesters on walls, to power devices.

Storage: Battery-free storage of energy and information is also a challenge. For example, new research points to the storage of harvested energy in masonry bricks [241], compressed air, etc., for building-scale energy storage. In the future, we could extend the thesis direction by exploring how we can build devices with such masonry bricks and how to enable these novel devices to perform intermittent computing for HCI? In addition to storage, power delivery and wireless power transfer through manufactured structures and buildings are essential.

Communication: Finally, novel manufacturing approaches, such as 3D printing and direct ink writing, are equally important. This thesis explored the use of these manufacturing advances to enable sensing in infrastructure materials. Beyond the thesis, we could explore how to enable cheap, large-scale computational building surfaces. For example, outside of this thesis work, we explored Duco [51], a large-scale robotic platform that sketches sensors, antennas, energy harvesters on walls, glass facades, etc., of buildings, turning such large surfaces into smart self-sustainable sensing skins. In the future, we could explore how a large-scale (low-frequency) printed antenna on building facades using Duco [51], could enable long-range building-to-building communication (using backscatter) of activities. These applications may make our infrastructure more resilient as they help with predictive maintenance of our aging built infrastructure.

9.2.2 Advancing computing architecture and circuitry for energy-efficient HCI & AI in the built environment



A recent study in 2019 [213] highlights that training specific deep neural networks can produce five times the CO_2 emissions associated with driving a car during its lifetime. Therefore, it is important to build energy-efficient deep learning hardware for HCI, especially considering the scale of the infrastructure (e.g., buildings, cities, etc.).

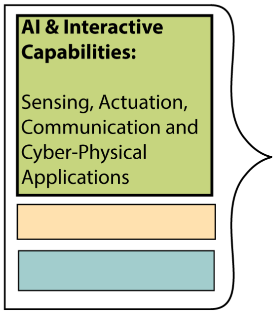
Although this thesis's main contribution on photonics and optical sensors has focused on long-range sensing and communication, there are exciting avenues for using photonics for the entire compute stack. For instance, logical operations, storage, etc., using nanophotonics enables energy-efficient computing with chip-scale optical instruments such as the Mach-Zender interferometer (MZI). Therefore, in the future, we could explore numerous environmentally conscious and energy-efficient AI/deep learning applications on a city scale using photonic computing.

Microwave Photonics: Finally, emerging high-frequency RF circuits, such as 5G or 6G, are great for fast communication; however, they suffer from low coverage. The design of metasurfaces [52] in the built environment that exploit electro-optical effects in 5G / 6G and optical communication networks may enable long-range detection of human interactions in the built environment.

With the decline of general purpose computing [158], next-generation computing nodes may enable new processing architectures such as non-von Neumann [105], and support intermittent computing. As the next step to this thesis work, we recently explored a self-powered material device [268] that responds to human interaction using an in-sensor analog computation approach with a network of organic photodiodes. In the future, we could explore how to support human-interaction detection through ML models such as Spike Neural Networks (SNNs) on non-von Neumann device architectures.

9.2.3 Cyber-Physical Applications: Accessibility, Construction, Sustainability & Global development

There are many potential application areas enabled by the computational infrastructure materials work proposed in this thesis. We go over some future areas of interest.



Accessibility: Nearly 1/3rd of the world's population suffers from some form of disability. Access to a built environment is crucial. This thesis took the first steps with Chapter 8, exploring insights from the field on how to design, manufacture, and deploy multi-modal sidewalk surfaces for blind and visually impaired users. In the future, we could extend this further to manufacture low-cost, self-powered, networked sensing surfaces/objects for people with vision impairments in the built environment. Beyond people with visual impairments, we could design devices in the infrastructure for people with mobility impairments. For example, our sidewalk infrastructure is often filled with uneven surfaces, potholes, etc.; capturing data cheaply about the health of such surfaces is crucial for infrastructure maintenance and access. There are nearly 2.5 million manual wheelchair users in the United States. Providing cheap battery-free, sustainable sensing, and mobile computing on a wheelchair can significantly improve quality of life and access to better services from the built environment, health tracking, etc.

Construction: Nearly 60% of the land that is about to be urbanized will be urbanized in the next 20 years, which means a lot of new construction and building. As we build our infrastructure, we could integrate more computational infrastructure materials to provide better services to the community's residents. For instance, as more and more sidewalk infrastructure is upgraded, computational infrastructure material solutions could help coordinate between robots and humans, who will eventually share that space. How we build and construct is also changing, and the US faces a nearly half-million worker shortage in construction jobs like masonry, carpentry, etc. Automation is expected to fill some gaps; adding intelligent functionality to infrastructure materials could go hand in hand with helping robots have perceptual capabilities as they build our infrastructure. When humans are needed and are working with computational infrastructure materials, novel interactive technologies, such as augmented reality, might help human construction better by guiding them and communicating with the infrastructure materials being used.

Sustainability & Global Development: This thesis makes efforts in Chapter 7 offering the opportunity to cut CO_2 emissions, providing a pathway to digitize infrastructure using a sustainable material (wood). Future applications of computational infrastructure materials could explore the possibility of developing self-powered soil materials [186] to monitor our wetland ecosystem to contribute to sustainability.

Finally, there are many challenges for global development where the confluence of novel computing, materials, and manufacturing technologies could enable frugal solutions that are much more accessible and democratized to a larger population. For example, providing sustainable, cheap, and long-lasting homes that meet the desires and aspirations of people remains a challenge. As a result, we face a challenge in the housing crisis around the world, and recent advances in 3D concrete printing have already made housing more accessible [38].

As we adopt such large-scale concrete printing technologies, in the future we could explore how computation can be printed on infrastructure materials as we build our infrastructure. Doing so may provide services to users immediately without needing any instrumentation (e.g., avoiding wiring, sensor installation, etc.). For instance, a 3D printed smart home may support applications like aging-in-place.

Bibliography

[1] Nasa armstrong fact sheet: Fiber optic sensing system | nasa. https://www.nasa.gov/centers/armstrong/news/FactSheets/FS-110-AFRC.html. (Accessed on 02/09/2020). 4.2

[2] Mataerial. http://mataerial.com, 2018. [Online; accessed 2018-04-05]. 2.1.3

[3] Minibuilders. http://iaac.net/printingrobots, 2018. [Online; accessed 2018-04-05]. 2.1.3

[4] ANISOPRINT. http://anisoprint.ru/, 2019. [Online; accessed 6-January-2019]. 5.6

[5] Baam - big area additive manufacturing, 2019. URL https://www.e-ci.com/baam. 4.1

[6] Boxzy home, 2019. URL https://boxzy.com/. 4.1

[7] Carbon-fiber Strength Data. https://static.markforged.com/markforged_composites_datasheet.pdf, 2019. [Online; accessed 6-January-2019]. 5.1

[8] Markforged Product Details. https://markforged.com/materials/composites/, 2019. [Online; accessed 6-January-2019]. 2.4.1, 5.2.1

[9] PLA Strength Data. http://tinyurl.com/PLAVoxel8, 2019. [Online; accessed 6-January-2019]. 5.1

[10] SLCOM1. https://envisiontec.com/3d-printers/slcom-1/slcom-1/, 2019. [Online; accessed 6-January-2019]. 2.4.1

[11] Objet30 pro desktop 3d printer for rapid prototyping, 2019. URL https://www.stratasys.com/3d-printers/objet30-pro. 4.1

[12] Voxel8. https://www.voxel8.com/, 2019. [Online; accessed 6-January-2019]. 2.4.1

[13] Fiber Bragg Grating Manufacturing Workstation, Apr 2020. URL https://www.newport.com/f/fiber-bragg-grating-workstation. [Online; accessed 27. Apr. 2020]. 4.3.2

[14] Viewpoint: Moore's law isn't broken - it's overheated | The Engineer, Nov 2020. URL https://www.theengineer.co.uk/viewpoint-moores-law-lightmatter. [Online; accessed 6. May 2021]. 3.2, 4.3.2

[15] Micron Optics, Apr 2020. URL http://www.micronoptics.com. [Online; accessed 27. Apr. 2020]. 4.3.2

[16] The Future of IoT: 10 Predictions about the Internet of Things | Norton, May 2021. URL https://us.norton.com/internetsecurity-iot-5-predictions-for-the-future-of-iot.html. [Online; accessed 6. May 2021]. 1.1

[17] The Future of Power Needs to be Exotic | Applied Materials, Apr 2021. URL https://www.appliedmaterials.com/nanochip/nanochip-fab-solutions/july-2019/the-future-of-power-needs-to-be-exotic. [Online; accessed 28. Apr. 2021]. 3.2

[18] An Airbnb I recently stayed at had hidden cameras in the bedrooms, my friends and I were recorded having sex. Anything I can do to have the footage deleted?, May 2021. URL https://old.reddit.com/r/legaladvice/comments/cx5uzr/an_airbnb_i_recently_stayed_at_had_hidden_cameras. [Online; accessed 6. May 2021]. 2.2.1

[19] Lightmatter, Apr 2021. URL https://lightmatter.co. [Online; accessed 28. Apr. 2021]. 3.2, 4.3.2

[20] Low Power Radio - General Information, September 2021. URL https://www.fcc.gov/media/radio/low-power-radio-general-information. [Online; accessed 11. Jul. 2022]. 7.4.2

[21] The influence of patents on 3D printing evolution - Creax, May 2021. URL https://creax.com/insights/the-influence-of-patents-on-3d-printing-evolution. [Online; accessed 6. May 2021]. 1.2.5

[22] Home Security Cameras | Wireless, Indoor & Outdoor HD WiFi Cameras, Apr 2021. URL https://ring.com/security-cameras. [Online; accessed 27. Apr. 2021]. 2.2.1

[23] Strategy Analytics: Global Smart Speaker Sales Cross 150 Million Units for 2020 Following Robust Q4 Demand, Mar 2021. URL https://www.businesswire.com/news/home/20210303005852/en/Strategy-Analytics-Global-Smart-Speaker-Sales-Cross-150-Million-Units-for-2020-Following-Robu [Online; accessed 6. May 2021]. 1.1

[24] When Things Start to Think - Google Books, May 2021. URL https://www.google.com/books/edition/When_Things_Start_to_Think/EU0Fh97hmksC?hl=en. [Online; accessed 6. May 2021]. 1.1

[25] Zensors | Cutting-Edge Computer Vision Technology | AI Cloud, Apr 2021. URL https://www.zensors.com. [Online; accessed 27. Apr. 2021]. 2.2.1

[26] tinySA | Main / HomePage, July 2022. URL https://www.tinysa.org/wiki. [Online; accessed 11. Jul. 2022]. 7.4.2

[27] Gregory D. Abowd. The Internet of Materials: A Vision for Computational Materials. *IEEE Pervasive Comput.*, 19(2):56–62, May 2020. ISSN 1558-2590. doi: 10.1109/MPRV.2020.2982475. 1.1, 9.1, 9.2.1

[28] Fadel Adib, Chen-Yu Hsu, Hongzi Mao, Dina Katabi, and Frédo Durand. Capturing the human figure through a wall. *ACM Trans. Graphics*, 34(6):1–13, Oct 2015.

ISSN 0730-0301. doi: 10.1145/2816795.2818072. 2.3.3

[29] Fadel Adib, Hongzi Mao, Zachary Kabelac, Dina Katabi, and Robert C. Miller. *Smart Homes that Monitor Breathing and Heart Rate*. Association for Computing Machinery, New York, NY, USA, Apr 2015. ISBN 978-1-45033145-6. doi: 10.1145/2702123.2702200. 2.3.3

[30] Francesco Amato, Hakki M. Torun, and Gregory D. Durgin. Beyond the limits of classic backscattering communications: A quantum tunneling RFID tag. In *2017 IEEE International Conference on RFID (RFID)*, pages 20–25. IEEE, May 2017. doi: 10.1109/RFID.2017.7945581. 1.2.2

[31] Byoungkwon An, Ye Tao, Jianzhe Gu, Tingyu Cheng, Xiang 'Anthony' Chen, Xiaoxiao Zhang, Wei Zhao, Youngwook Do, Shigeo Takahashi, Hsiang-Yun Wu, Teng Zhang, and Lining Yao. *Thermorph: Democratizing 4D Printing of Self-Folding Materials and Interfaces*. Association for Computing Machinery, New York, NY, USA, Apr 2018. ISBN 978-1-45035620-6. doi: 10.1145/3173574.3173834. 2.4.2

[32] Nivedita Arora, Steven L Zhang, Fereshteh Shahmiri, Diego Osorio, Yi-Cheng Wang, Mohit Gupta, Zhengjun Wang, Thad Starner, Zhong Lin Wang, and Gregory D Abowd. Saturn: A thin and flexible self-powered microphone leveraging triboelectric nanogenerator. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, 2(2):1–28, 2018. 2.3.1

[33] Nivedita Arora, Ali Mirzazadeh, Injoo Moon, Charles Ramey, Yuhui Zhao, Daniela C. Rodriguez, Gregory D. Abowd, and Thad Starner. MARS: Nano-Power Battery-free Wireless Interfaces for Touch, Swipe and Speech Input. In *UIST '21: The 34th Annual ACM Symposium on User Interface Software and Technology*, pages 1305–1325. Association for Computing Machinery, New York, NY, USA, October 2021. ISBN 978-1-45038635-7. doi: 10.1145/3472749.3474823. 2.3.1

[34] Tyler J Arsenault, Ajit Achuthan, Pier Marzocca, Chiara Grappasonni, and Giuliano Coppotelli. Development of a fbg based distributed strain sensor system for wind turbine structural health monitoring. *Smart Materials and Structures*, 22(7): 075027, 2013. 2.4.1

[35] Rodrigo R de Assis and Ildefonso Bianchi. Analysis of microstrip antennas on carbon fiber composite material. *Journal of Microwaves, Optoelectronics and Electromagnetic Applications*, 11(1):154–161, 2012. 2.4.1

[36] Moritz Bächer, Benjamin Hepp, Fabrizio Pece, Paul G Kry, Bernd Bickel, Bernhard Thomaszewski, and Otmar Hilliges. Defsense: Computational design of customized deformable input devices. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pages 3806–3816. ACM, 2016. 2.4.1

[37] Abdelkareem Bedri, Richard Li, Malcolm Haynes, Raj Prateek Kosaraju, Ishaan Grover, Temiloluwa Prioleau, Min Yan Beh, Mayank Goel, Thad Starner, and Gregory Abowd. Earbit: using wearable sensors to detect eating episodes in unconstrained environments. *Proceedings of the ACM on interactive, mobile, wearable*

and ubiquitous technologies, 1(3):1–20, 2017. 2.2.2

[38] Claretta Bellamy. How 3D printing can be the solution to the nation's affordable housing crisis. *NBC News*, January 2022. URL https://www.nbcnews.com/news/nbcblk/3d-printing-can-solution-nations-affordable-housing-crisis-rcna10725. 9.2.3

[39] Abhinav Bhardwaj, Scott Z. Jones, Negar Kalantar, Zhijian Pei, John Vickers, Timothy Wangler, Pablo Zavattieri, and Na Zou. Additive Manufacturing Processes for Infrastructure Construction: A Review. *J. Manuf. Sci. Eng.*, 141(9), Sep 2019. ISSN 1087-1357. doi: 10.1115/1.4044106. 2.1.1

[40] Amelie Bonde, Shijia Pan, Hae Young Noh, and Pei Zhang. Deskbuddy: an office activity detection system: demo abstract. In *Proceedings of the 18th International Conference on Information Processing in Sensor Networks*, pages 352–353, 2019. 2.2.3

[41] Michael Brambring. Mobility and orientation processes of the blind. In *Electronic spatial sensing for the blind*, pages 493–508. Springer, 1985. 8.1

[42] Alan Bränzel, Christian Holz, Daniel Hoffmann, Dominik Schmidt, Marius Knaust, Patrick Lühne, René Meusel, Stephan Richter, and Patrick Baudisch. Gravityspace: Tracking users and their poses in a smart room using a pressure-sensing floor. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '13, pages 725–734, New York, NY, USA, 2013. ACM. ISBN 978-1-4503-1899-0. doi: 10.1145/2470654.2470757. URL http://doi.acm.org/10.1145/2470654.2470757. 2.2.3

[43] Virginia Braun and Victoria Clarke. Using thematic analysis in psychology. *Qualitative research in psychology*, 3(2):77–101, 2006. 8.1.1

[44] Michael Buettner, Richa Prasad, Matthai Philipose, and David Wetherall. Recognizing daily activities with rfid-based sensors. In *Proceedings of the 11th international conference on Ubiquitous computing*, pages 51–60, 2009. 2.3.1

[45] Fabian Caba Heilbron, Victor Escorcia, Bernard Ghanem, and Juan Carlos Niebles. Activitynet: A large-scale video benchmark for human activity understanding. In *Proceedings of the ieee conference on computer vision and pattern recognition*, pages 961–970, 2015. 2.2.1

[46] Megan Campbell, Cynthia Bennett, Caitlin Bonnar, and Alan Borning. Where's my bus stop? supporting independence of blind transit riders with stopinfo. In *Proceedings of the 16th international ACM SIGACCESS conference on Computers & accessibility*, pages 11–18, 2014. 8.3.6

[47] Kristy�na Čápová, Lukáš Velebil, and Jan Včelák. Laboratory and in-situ testing of integrated fbg sensors for shm for concrete and timber structures. *Sensors*, 20 (6):1661, 2020. 2.4.1

[48] Jillian Carr and Jennifer L Doleac. The geography, incidence, and underreporting of gun violence: new evidence using shotspotter data. *Incidence, and Underreporting of Gun Violence: New Evidence Using Shotspotter Data (April 26, 2016)*,

2016. 2.2.2

[49] Tingyu Cheng, Koya Narumi, Youngwook Do, Yang Zhang, Tung D. Ta, Takuya Sasatani, Eric Markvicka, Yoshihiro Kawahara, Lining Yao, Gregory D. Abowd, and HyunJoo Oh. Silver Tape: Inkjet-Printed Circuits Peeled-and-Transferred on Versatile Substrates. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.*, 4(1): 1–17, Mar 2020. ISSN 2474-9567. doi: 10.1145/3381013. 2.4.1

[50] Tingyu Cheng, Koya Narumi, Youngwook Do, Yang Zhang, Tung D Ta, Takuya Sasatani, Eric Markvicka, Yoshihiro Kawahara, Lining Yao, Gregory D Abowd, et al. Silver tape: Inkjet-printed circuits peeled-and-transferred on versatile substrates. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, 4(1):1–17, 2020. 2.4.1

[51] Tingyu Cheng, Bu Li, Yang Zhang, Yunzhi Li, Charles Ramey, Eui Min Jung, Yepu Cui, Sai Ganesh Swaminathan, Youngwook Do, Manos Tentzeris, et al. Duco: Autonomous large-scale direct-circuit-writing (dcw) on vertical everyday surfaces using a scalable hanging plotter. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, 5(3):1–25, 2021. 9.2.1

[52] Kun Woo Cho, Mohammad H Mazaheri, Jeremy Gummeson, Omid Abari, and Kyle Jamieson. mmwall: A reconfigurable metamaterial surface for mmwave networks. In *Proceedings of the 22nd International Workshop on Mobile Computing Systems and Applications*, pages 119–125, 2021. 9.2.2

[53] Brian Clarkson, Nitin Sawhney, and Alex Pentland. Auditory context awareness via wearable computing. *Energy*, 400(600):20, 1998. 2.2.2

[54] Sunny Consolvo, Beverly Harrison, Ian Smith, Mike Y. Chen, Katherine Everitt, Jon Froehlich, and James A. Landay. Conducting In Situ Evaluations for and With Ubiquitous Computing Technologies. *International Journal of Human–Computer Interaction*, 22(1-2):103–118, Apr 2007. ISSN 1044-7318. doi: 10.1080/10447310709336957. 1.1

[55] Contributors to Wikimedia projects. Great Chicago Fire - Wikipedia, June 2022. URL https://en.wikipedia.org/w/index.php?title=Great_Chicago_Fire&oldid=1095710835. [Online; accessed 11. Jul. 2022]. 7.1

[56] Scott Curran, Paul Chambon, Randall Lind, Lonnie Love, Robert Wagner, Steven Whitted, David Smith, Brian Post, Ronald Graves, Craig Blue, et al. Big area additive manufacturing and hardware-in-the-loop for rapid vehicle powertrain prototyping: A case study on the development of a 3-d-printed shelby cobra. Technical report, SAE Technical Paper, 2016. 2.1.1

[57] Spyridon-Nektarios Daskalakis, Stylianos D Assimonis, Eleftherios Kampianakis, and Aggelos Bletsas. Soil moisture scatter radio networking with low power. *IEEE Transactions on Microwave Theory and Techniques*, 64(7):2338–2346, 2016. 2.3.2

[58] Spyridon Nektarios Daskalakis, George Goussetis, Stylianos D Assimonis, Manos M Tentzeris, and Apostolos Georgiadis. A uw backscatter-morse-leaf sen-

sor for low-power agricultural wireless sensor networks. *IEEE Sensors Journal*, 18 (19):7889–7898, 2018. 2.3.2

[59] Davis S De Lorenzo and ML Hull. Quantification of structural loading during off-road cycling. *Journal of Biomechanical Engineering*, 121(4):399–405, 1999. 5.5.1

[60] Yuliang Deng, Michael G Pecht, Joseph A Swift, and Stanley J Wallace. Carbon fiber-based grid array interconnects. *IEEE Transactions on Components and Packaging Technologies*, 30(4):716–723, 2007. 2.4.1

[61] Charalampos Doukas and Ilias Maglogiannis. *Advanced patient or elder fall detection based on movement and sound data*. IEEE, Hungary, Jan 2008. ISBN 978-963-9799-15-8. doi: 10.1109/PCTHEALTH.2008.4571042. 2.2.2

[62] Chad E. Duty, Vlastimil Kunc, Brett Compton, Brian Post, Donald Erdman, Rachel Smith, Randall Lind, Peter Lloyd, and Lonnie Love. Structure and mechanical behavior of Big Area Additive Manufacturing (BAAM) materials. *Rapid Prototyping Journal*, Jan 2017. doi: 10.1108/RPJ-12-2015-0183. 2.1.1

[63] W. Keith Edwards and Rebecca E. Grinter. At Home with Ubiquitous Computing: Seven Challenges. In *UbiComp '01: Proceedings of the 3rd international conference on Ubiquitous Computing*, pages 256–272. Springer-Verlag, Berlin, Germany, Sep 2001. ISBN 978-354042614. doi: 10.5555/647987.741327. 1.1

[64] A. J. Eronen, V. T. Peltonen, J. T. Tuomi, A. P. Klapuri, S. Fagerlund, T. Sorsa, G. Lorho, and J. Huopaniemi. Audio-based context recognition. *Trans. Audio, Speech and Lang. Proc.*, 14(1):321–329, December 2006. ISSN 1558-7916. doi: 10.1109/TSA.2005.854103. URL http://dx.doi.org/10.1109/TSA.2005.854103. 2.2.3

[65] RW Evans. Design guidelines for shielding effectiveness, current carrying capability, and the enhancement of conductivity of composite materials. 1997. 2.4.1

[66] J. Fagert, M. Mirshekari, S. Pan, P. Zhang, and H.Y. Noh. Characterizing left-right gait balance using footstep-induced structural vibrations. In *SPIE 10168, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems*, volume 10168, pages 10168 – 10168 – 9, 2017. 2.2.3

[67] Richard Feynman. There's plenty of room at the bottom. In *Feynman and computation*, pages 63–76. CRC Press, 2018. 1.1

[68] Richard P Feynman. There's plenty of room at the bottom. 1.1

[69] James Fogarty, Carolyn Au, and Scott E. Hudson. Sensing from the basement: A feasibility study of unobtrusive and low-cost home activity recognition. In *Proceedings of the 19th Annual ACM Symposium on User Interface Software and Technology*, UIST '06, pages 91–100, New York, NY, USA, 2006. ACM. ISBN 1-59593-313-1. doi: 10.1145/1166253.1166269. URL http://doi.acm.org/10.1145/1166253.1166269. 2.2.3

[70] Sean Follmer, Daniel Leithinger, Alex Olwal, Akimitsu Hogge, and Hiroshi Ishii.

inFORM: dynamic physical affordances and constraints through shape and object actuation. Association for Computing Machinery, New York, NY, USA, Oct 2013. ISBN 978-1-45032268-3. doi: 10.1145/2501988.2502032. 2.4.2

[71] Jon E. Froehlich, Eric Larson, Tim Campbell, Conor Haggerty, James Fogarty, and Shwetak N. Patel. Hydrosense: Infrastructure-mediated single-point sensing of whole-home water activity. In *Proceedings of the 11th International Conference on Ubiquitous Computing*, UbiComp '09, pages 235–244, New York, NY, USA, 2009. ACM. ISBN 978-1-60558-431-7. doi: 10.1145/1620545.1620581. URL http://doi.acm.org/10.1145/1620545.1620581. 2.2.3

[72] Charis J Gantes. *Deployable structures: analysis and design*. Wit Press, 2001. 6.2

[73] Neil Gershenfeld, Raffi Krikorian, and Danny Cohen. The Internet of Things. *Scientific American*, 291(4):76–81, October 2004. ISSN 0036-8733. doi: 10.1038/scientificamerican1004-76. URL https://www.scientificamerican.com/article/the-internet-of-things. 1.1

[74] Nicholas A Giudice. Navigating without vision: Principles of blind spatial cognition. In *Handbook of behavioral and cognitive geography*. Edward Elgar Publishing, 2018. 8.2.2

[75] Reginald G Golledge, Roberta L Klatzky, and Jack M Loomis. Cognitive mapping and wayfinding by adults without vision. In *The construction of cognitive maps*, pages 215–246. Springer, 1996. 8.2.2

[76] Nan-Wei Gong, Steve Hodges, and Joseph A Paradiso. Leveraging conductive inkjet technology to build a scalable and versatile surface for ubiquitous sensing. In *Proceedings of the 13th international conference on Ubiquitous computing*, pages 45–54, 2011. 2.2.3

[77] Nan-Wei Gong, Jürgen Steimle, Simon Olberding, Steve Hodges, Nicholas Edward Gillian, Yoshihiro Kawahara, and Joseph A Paradiso. Printsense: a versatile sensing technique to support multimodal flexible surface interaction. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 1407–1410, 2014. 2.4.1

[78] Fabio Gramazio, Matthias Kohler, and Silvan Oesterle. Encoding material. *Architectural Design*, 80(4):108–115, 2010. 2.1.3

[79] Jonathan Greig. IoT industry projected to have economic impact of $11 trillion by 2025. *TechRepublic*, May 2019. URL https://www.techrepublic.com/article/iot-industry-projected-to-have-economic-impact-of-11-trillion-by-2025. 1.1

[80] Daniel Groeger and Jürgen Steimle. Lasec: Instant fabrication of stretchable circuits using a laser cutter. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, pages 1–14, 2019. 2.4.1

[81] Daniel Groeger and Jürgen Steimle. ObjectSkin: Augmenting Everyday Objects with Hydroprinted Touch Sensors and Displays. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.*, 1(4):1–23, Jan 2018. ISSN 2474-9567. doi:

10.1145/3161165. 2.4.1

[82] Tobias Grosse-Puppendahl, Christian Holz, Gabe Cohn, Raphael Wimmer, Oskar Bechtold, Steve Hodges, Matthew S Reynolds, and Joshua R Smith. Finding common ground: A survey of capacitive sensing in human-computer interaction. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, pages 3293–3315. ACM, 2017. 5.1, 5.4, 6.2, 6.7

[83] Anhong Guo, Anuraag Jain, Shomiron Ghose, Gierad Laput, Chris Harrison, and Jeffrey P Bigham. Crowd-ai camera sensing in the real world. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, 2(3):1–20, 2018. 2.2.1

[84] Mark Guttag and Mary C Boyce. Locally and dynamically controllable surface topography through the use of particle-enhanced soft composites. *Advanced Functional Materials*, 25(24):3641–3647, 2015. 8.5.1

[85] Norman Hack and Willi Viktor Lauer. Mesh-Mould: Robotically Fabricated Spatial Meshes as Reinforced Concrete Formwork. *Archit. Design*, 84(3):44–53, May 2014. ISSN 0003-8504. doi: 10.1002/ad.1753. 2.1.2

[86] A. Hanaor and R. Levy. Evaluation of Deployable Structures for Space Enclosures. *Int. J. Space Struct.*, 16(4):211–229, Dec 2001. ISSN 0956-0599. doi: 10.1260/026635101760832172. 3.4

[87] Beverly L Harrison, Kenneth P Fishkin, Anuj Gujar, Carlos Mochon, and Roy Want. Squeeze me, hold me, tilt me! an exploration of manipulative user interfaces. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 17–24. ACM Press/Addison-Wesley Publishing Co., 1998. 6.2

[88] Felix Heibeck, Basheer Tome, Clark Della Silva, and Hiroshi Ishii. *uniMorph: Fabricating Thin Film Composites for Shape-Changing Interfaces*. Association for Computing Machinery, New York, NY, USA, Nov 2015. ISBN 978-1-45033779-3. doi: 10.1145/2807442.2807472. 2.4.2

[89] Felix Heibeck, Basheer Tome, Clark Della Silva, and Hiroshi Ishii. unimorph: Fabricating thin film composites for shape-changing interfaces. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*, pages 233–242, 2015. 2.4.1

[90] Steve Hodges, Nicolas Villar, Nicholas Chen, Tushar Chugh, Jie Qi, Diana Nowacka, and Yoshihiro Kawahara. Circuit stickers: peel-and-stick construction of interactive electronic prototypes. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 1743–1746. ACM, 2014. 2.4.1

[91] Chris Holshouser, Clint Newell, Sid Palas, Lonnie J Love, Vlastimil Kunc, Randall F Lind, Peter D Lloyd, John C Rowe, Craig A Blue, Chad E Duty, et al. Out of bounds additive manufacturing. *Advanced Materials and Processes*, 171(3), 2013. 2.1.1

[92] Hayley Hung, Gwenn Englebienne, and Jeroen Kools. Classifying social actions with a single accelerometer. In *Proceedings of the 2013 ACM international joint*

conference on Pervasive and ubiquitous computing, pages 207–210, 2013. 2.2.2

[93] DOOIL Hwang and Behrokh Khoshnevis. An innovative construction process-contour crafting (cc). In *22nd International Symposium on Automation and Robotics in Construction*, volume 90111. ISARC, 2005. 2.1.1

[94] Daniele Inaudi. *Optical Fiber Sensors for Dam and Levee Monitoring and Damage Detection*, pages 91–120. 11 2019. ISBN 978-3-030-27366-8. doi: 10.1007/978-3-030-27367-5_5. 4.2

[95] Daniele Inaudi and Branko Glisic. Long-Range Pipeline Monitoring by Distributed Fiber Optic Sensing. *American Society of Mechanical Engineers Digital Collection*, pages 763–772, Oct 2008. doi: 10.1115/IPC2006-10287. 4.2

[96] Alexandra Ion, Johannes Frohnhofen, Ludwig Wall, Robert Kovacs, Mirela Alistar, Jack Lindsay, Pedro Lopes, Hsiang-Ting Chen, and Patrick Baudisch. Metamaterial mechanisms. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*, UIST '16, pages 529–539, New York, NY, USA, 2016. ACM. ISBN 978-1-4503-4189-9. doi: 10.1145/2984511.2984540. URL http://doi.acm.org/10.1145/2984511.2984540. 4.1

[97] Alexandra Ion, Johannes Frohnhofen, Ludwig Wall, Robert Kovacs, Mirela Alistar, Jack Lindsay, Pedro Lopes, Hsiang-Ting Chen, and Patrick Baudisch. Metamaterial mechanisms. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*, pages 529–539. ACM, 2016. 2.4.2

[98] Alexandra Ion, Ludwig Wall, Robert Kovacs, and Patrick Baudisch. Digital mechanical metamaterials. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, pages 977–988. ACM, 2017. 2.4.2

[99] Alexandra Ion, Robert Kovacs, Oliver S. Schneider, Pedro Lopes, and Patrick Baudisch. Metamaterial textures. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, CHI '18, pages 336:1–336:12, New York, NY, USA, 2018. ACM. ISBN 978-1-4503-5620-6. doi: 10.1145/3173574.3173910. URL http://doi.acm.org/10.1145/3173574.3173910. 4.1

[100] Hiroshi Ishii, Craig Wisneski, Julian Orbanes, Ben Chun, and Joe Paradiso. Pingpongplus: design of an athletic-tangible interface for computer-supported cooperative play. In *Proceedings of the SIGCHI conference on Human Factors in Computing Systems*, pages 394–401. ACM, 1999. 2.2.3

[101] Vikram Iyer, Justin Chan, and Shyamnath Gollakota. 3d printing wireless connected objects. ACM, 2017. 2.3.1

[102] Vikram Iyer, Justin Chan, Ian Culhane, Jennifer Mankoff, and Shyamnath Gollakota. Wireless analytics for 3d printed objects. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*, pages 141–152, 2018. 2.3.1

[103] William Henry Jacobson. *The art and science of teaching orientation and mobility to persons with visual impairments*. American Foundation for the Blind, 1993. 8.1

[104] Eun-Beom Jeon, Takahiro Fujimura, Kosuke Takahashi, and Hak-Sung Kim. An investigation of contact resistance between carbon fiber/epoxy composite laminate and printed silver electrode for damage monitoring. *Composites Part A: Applied Science and Manufacturing*, 66:193–200, 2014. 2.4.1

[105] R. Colin Johnson. Non-Von Neumann Computers Providing Brain-Like Functionality, November 2017. URL https://cacm.acm.org/news/222940-non-von-neumann-computers-providing-brain-like-functionality/fulltext. [Online; accessed 11. Jul. 2022]. 9.2.2

[106] J. M. Kahn, R. H. Katz, and K. S. J. Pister. *Next century challenges: mobile networking for "Smart Dust"*. Association for Computing Machinery, New York, NY, USA, Aug 1999. ISBN 978-158113142. doi: 10.1145/313451.313558. 1.2.2

[107] Hsin-Liu Kao, Christian Holz, Asta Roseway, Andres Calvo, and Chris Schmandt. Duoskin: rapidly prototyping on-skin user interfaces using skin-friendly materials. In *Proceedings of the 2016 ACM International Symposium on Wearable Computers*, pages 16–23, 2016. 2.4.1

[108] Cansu Karatas, Boray Degerliyurt, Yavuz Yaman, and Melin Sahin. Fibre bragg grating sensor applications for structural health monitoring. *Aircraft Engineering and Aerospace Technology*, 2018. 2.4.1

[109] Raman Kashyap. *Fiber bragg gratings*. Academic press, Cambridge, MA, 2009. 4.3.3

[110] Kunihiro Kato and Homei Miyashita. Extensionsticker: A proposal for a striped pattern sticker to extend touch interfaces and its assessment. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, CHI '15, page 1851–1854, New York, NY, USA, 2015. Association for Computing Machinery. ISBN 9781450331456. doi: 10.1145/2702123.2702500. URL https://doi.org/10.1145/2702123.2702500. 2.4.1

[111] Yoshihiro Kawahara, Hoseon Lee, and Manos M Tentzeris. Sensprout: Inkjet-printed soil moisture and leaf wetness sensor. In *Proceedings of the 2012 ACM Conference on Ubiquitous Computing*, pages 545–545, 2012. 2.4.1

[112] Yoshihiro Kawahara, Steve Hodges, Benjamin S Cook, Cheng Zhang, and Gregory D Abowd. Instant inkjet circuits: lab-based inkjet printing to support rapid prototyping of ubicomp devices. In *Proceedings of the 2013 ACM international joint conference on Pervasive and ubiquitous computing*, pages 363–372. ACM, 2013. 2.4.1

[113] Markus Kayser, Levi Cai, Christoph Bader, Sara Falcone, Nassia Inglessis, Barrak Darweesh, João Costa, and Neri Oxman. FIBERBOTS: Design and Digital Fabrication of Tubular Structures Using Robot Swarms. In *Robotic Fabrication in Architecture, Art and Design 2018*, pages 285–296. Springer, Cham, Switzerland, Aug 2018. ISBN 978-3-319-92293-5. doi: 10.1007/978-3-319-92294-2_22. 2.1.3

[114] Brett E. Kelly, Indrasen Bhattacharya, Hossein Heidari, Maxim Shusteff, Christo-

pher M. Spadaccini, and Hayden K. Taylor. Volumetric additive manufacturing via tomographic reconstruction. *Science*, 363(6431):1075–1079, Mar 2019. ISSN 0036-8075. doi: 10.1126/science.aau7114. 2.1.1

[115] Arshad Khan, Joan Sol Roo, Tobias Kraus, and Jürgen Steimle. Soft inkjet circuits: Rapid multi-material fabrication of soft circuits using a commodity inkjet printer. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*, pages 341–354, 2019. 2.4.1

[116] Behrokh Khoshnevis and Rosanne Dutton. Innovative Rapid Prototyping Process Makes Large Sized, Smooth Surfaced Complex Shapes in a Wide Variety of Materials. *Mater. Technol.*, 13(2):53–56, Jan 1998. ISSN 1066-7857. doi: 10.1080/10667857.1998.11752766. 2.1.1

[117] Dae Shik Kim, Robert Wall Emerson, and Eleni Gaves. Travel in adverse winter weather conditions by blind pedestrians: effect of cane tip design on travel on snow. *Journal of visual impairment & blindness*, 110(1):53–58, 2016. 8.1

[118] By Jessica Klingelfuss. MegaFaces: Architect Asif Khan's kinetic façade for the Sochi 2014 Winter Olympics. *Wallpaper∗*, Dec 2015. URL https://www.wallpaper.com/architecture/megafaces-architect-asif-khans-kinetic-faade-for-the-sochi-2014-winter-olympics. 2.4.2

[119] Robert Kovacs, Anna Seufert, Ludwig Wall, Hsiang-Ting Chen, Florian Meinel, Willi Müller, Sijing You, Maximilian Brehm, Jonathan Striebel, Yannis Kommana, et al. Trussfab: Fabricating sturdy large-scale structures on desktop 3d printers. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, pages 2606–2616. ACM, 2017. 2.1.4

[120] Robert Kovacs, Alexandra Ion, Pedro Lopes, Tim Oesterreich, Johannes Filter, Philipp Otto, Tobias Arndt, Nico Ring, Melvin Witte, Anton Synytsia, and et al. Trussformer: 3d printing large kinetic structures. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*, UIST '18, pages 113–125, New York, NY, USA, 2018. Association for Computing Machinery. ISBN 9781450359481. doi: 10.1145/3242587.3242607. URL https://doi.org/10.1145/3242587.3242607. 2.1.5

[121] Benjamin Lafreniere, Tovi Grossman, Fraser Anderson, Justin Matejka, Heather Kerrick, Danil Nagy, Lauren Vasey, Evan Atherton, Nicholas Beirne, Marcelo H Coelho, et al. Crowdsourced fabrication. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*, pages 15–28. ACM, 2016. 2.1.4

[122] Gierad Laput and Chris Harrison. *Sensing Fine-Grained Hand Activity with Smartwatches*. Association for Computing Machinery, New York, NY, USA, May 2019. ISBN 978-1-45035970-2. doi: 10.1145/3290605.3300568. 2.2.2

[123] Gierad Laput and Chris Harrison. Surfacesight: A new spin on touch, user, and

object sensing for iot experiences. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, CHI '19, pages 329:1–329:12, New York, NY, USA, 2019. ACM. ISBN 978-1-4503-5970-2. doi: 10.1145/3290605.3300559. URL http://doi.acm.org/10.1145/3290605.3300559. 2.2.3

[124] Gierad Laput and Chris Harrison. Exploring the efficacy of sparse, general-purpose sensor constellations for wide-area activity sensing. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, 3(2): 55, 2019. 2.2.3, 4.7.1

[125] Gierad Laput, Eric Brockmeyer, Scott E Hudson, and Chris Harrison. Acoustruments: Passive, acoustically-driven, interactive controls for handheld devices. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, pages 2161–2170. ACM, 2015. 6.2, 6.3.2

[126] Gierad Laput, Walter S Lasecki, Jason Wiese, Robert Xiao, Jeffrey P Bigham, and Chris Harrison. Zensors: Adaptive, rapidly deployable, human-intelligent sensor feeds. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, pages 1935–1944, 2015. 2.2.1

[127] Gierad Laput, Robert Xiao, and Chris Harrison. Viband: High-fidelity bio-acoustic sensing using commodity smartwatch accelerometers. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*, pages 321–333, 2016. 2.2.2

[128] Gierad Laput, Yang Zhang, and Chris Harrison. Synthetic sensors: Towards general-purpose sensing. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, pages 3986–3999. ACM, 2017. 2.2.3, 4.7.1

[129] Gierad Laput, Karan Ahuja, Mayank Goel, and Chris Harrison. Ubicoustics: Plug-and-play acoustic activity recognition. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*, UIST '18, pages 213–224, New York, NY, USA, 2018. ACM. ISBN 978-1-4503-5948-1. doi: 10.1145/3242587.3242609. URL http://doi.acm.org/10.1145/3242587.3242609. 2.2.3

[130] Joanne Leong, Patrick Parzer, Florian Perteneder, Teo Babic, Christian Rendl, Anita Vogl, Hubert Egger, Alex Olwal, and Michael Haller. procover: sensory augmentation of prosthetic limbs using smart textile covers. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*, pages 335–346. ACM, 2016. 2.4.1

[131] Hanchuan Li, Can Ye, and Alanson P Sample. Idsense: A human object interaction detection system based on passive uhf rfid. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, pages 2555–2564, 2015. 2.3.1

[132] Hanchuan Li, Eric Brockmeyer, Elizabeth J Carter, Josh Fromm, Scott E Hudson, Shwetak N Patel, and Alanson Sample. Paperid: A technique for drawing functional battery-free wireless interfaces on paper. In *Proceedings of the 2016 CHI*

Conference on Human Factors in Computing Systems, pages 5885–5896, 2016. 2.3.1, 2.4.1

[133] Lin Li, Jihong Yan, and Zhongwen Xing. Energy requirements evaluation of milling machines based on thermal equilibrium and empirical modelling. *J. Cleaner Prod.*, 52:113–121, Aug 2013. ISSN 0959-6526. doi: 10.1016/j.jclepro.2013.02.039. 2.1.2

[134] Xiang Li, Daqing Zhang, Qin Lv, Jie Xiong, Shengjie Li, Yue Zhang, and Hong Mei. IndoTrack: Device-Free Indoor Human Tracking with Commodity Wi-Fi. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.*, 1(3):1–22, Sep 2017. ISSN 2474-9567. doi: 10.1145/3130940. 2.3.3

[135] Xinyu Li, Yuan He, and Xiaojun Jing. A Survey of Deep Learning-Based Human Activity Recognition in Radar. *Remote Sens.*, 11(9):1068, May 2019. ISSN 2072-4292. doi: 10.3390/rs11091068. 2.3.3

[136] Yang Li, Jason I. Hong, and James A. Landay. Design Challenges and Principles for Wizard of Oz Testing of Location-Enhanced Applications. *IEEE Pervasive Comput.*, 6(2):70–75, Apr 2007. ISSN 1558-2590. doi: 10.1109/MPRV.2007.28. 1.1

[137] Stephen M Lipka. Electrochemical capacitors utilizing low surface area carbon fiber. *IEEE Aerospace and Electronic Systems Magazine*, 12(7):27–30, 1997. 2.4.1

[138] Shengli Liu. Carbon fiber contactor in polymer resistive position sensors. In *Electrical Contacts, 2001. Proceedings of the Forty-Seventh IEEE Holm Conference on*, pages 282–287. IEEE, 2001. 2.4.1

[139] Ena Lloret-Fritschi, Timothy Wangler, Lukas Gebhard, Jaime Mata-Falcón, Sara Mantellato, Fabio Scotto, Joris Burger, Anna Szabo, Nicholas Ruffray, Lex Reiter, Federica Boscaro, Walter Kaufmann, Matthias Kohler, Fabio Gramazio, and Robert Flatt. From Smart Dynamic Casting to a growing family of Digital Casting Systems. *Cem. Concr. Res.*, 134:106071, Aug 2020. ISSN 0008-8846. doi: 10.1016/j.cemconres.2020.106071. 2.1.2

[140] Joanne Lo, Doris Jung Lin Lee, Nathan Wong, David Bui, and Eric Paulos. Skintillates: Designing and creating epidermal interactions. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems*, pages 853–864, 2016. 2.4.1

[141] Jack M. Loomis, Roberta L. Klatzky, and Nicholas A. Giudice. Representing 3D Space in Working Memory: Spatial Images from Vision, Hearing, Touch, and Language. *DigitalCommons@UMaine*, page 131, 2013. doi: 10.1007/978-1-4614-5879-1_8. 8.2.2

[142] Linjie Luo, Ilya Baran, Szymon Rusinkiewicz, and Wojciech Matusik. Chopper: partitioning models into 3d-printable parts. 2012. 2.1.4

[143] Kevin Lynch. The image of the city. boston: Mass, ee. uu, 1960. 8.2.2

[144] Ramin Madarshahian, Juan M Caicedo, and Diego Arocha Zambrana. Benchmark problem for human activity identification using floor vibrations. *Expert Systems*

with Applications, 62:263–272, 2016. 2.2.3

[145] Pankar K Mallick. *Fiber-reinforced composites: materials, manufacturing, and design*. CRC press, 2007. 5.6

[146] Eric Markvicka, Guanyun Wang, Yi-Chin Lee, Gierad Laput, Carmel Majidi, and Lining Yao. Electrodermis: Fully untethered, stretchable, and highly-customizable electronic bandages. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, pages 1–10, 2019. 2.4.1

[147] Shota Mashiyama, Jihoon Hong, and Tomoaki Ohtsuki. Activity recognition using low resolution infrared array sensor. In *2015 IEEE International Conference on Communications (ICC)*, pages 495–500. IEEE, 2015. 2.2.1

[148] *SM-130 Optical Sensing Interrogator*. Micron Optics, 2009. 4.3.2

[149] Kelly Minner. Spencer Dock Bridge / Amanda Levete Architects. *ArchDaily*, Sep 2017. URL https://www.archdaily.com/96400/spencer-dock-bridge-amanda-levete-architects. 2.1.2

[150] Mostafa Mirshekari, Shijia Pan, Jonathon Fagert, Eve M Schooler, Pei Zhang, and Hae Young Noh. Occupant localization using footstep-induced structural vibration. *Mechanical Systems and Signal Processing*, 112:77–97, 2018. 4.6.1

[151] Mostafa Mirshekari, Jonathon Fagert, Shijia Pan, Pei Zhang, and Hae Young Noh. Step-level occupant detection across different structures through footstep-induced floor vibration using model transfer. *Journal of Engineering Mechanics*, 146(3):04019137, 2020. 2.2.3

[152] Tomomi Mizuno, Arisa Nishidate, Katsumi Tokuda, and ARAI Kunijiro. Installation errors and corrections in tactile ground surface indicators in europe, america, oceania and asia. *IATSS research*, 32(2):68–80, 2008. (document), 8.1

[153] Jörg Müller, Dieter Eberle, and Constantin Schmidt. Baselase: An interactive focus+ context laser floor. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, pages 3869–3878. ACM, 2015. 2.2.3

[154] Saman Naderiparizi, Aaron N Parks, Zerina Kapetanovic, Benjamin Ransford, and Joshua R Smith. Wispcam: A battery-free rfid camera. In *2015 IEEE International Conference on RFID (RFID)*, pages 166–173. IEEE, 2015. 2.3.2

[155] Steven Nagels, Raf Ramakers, Kris Luyten, and Wim Deferme. Silicone devices: A scalable diy approach for fabricating self-contained multi-layered soft circuits using microfluidics. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, pages 1–13, 2018. 2.4.1

[156] Ken Nakagaki, Artem Dementyev, Sean Follmer, Joseph A. Paradiso, and Hiroshi Ishii. *ChainFORM: A Linear Integrated Modular Hardware System for Shape Changing Interfaces*. Association for Computing Machinery, New York, NY, USA, Oct 2016. ISBN 978-1-45034189-9. doi: 10.1145/2984511.2984587. 2.4.2

[157] Satoshi Nakamaru, Ryosuke Nakayama, Ryuma Niiyama, and Yasuaki Kakehi.

Foamsense: Design of three dimensional soft sensors with porous materials. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*, pages 437–447. ACM, 2017. 2.4.1

[158] Svenja Spanuth Neil C. Thompson. The Decline of Computers as a General Purpose Technology, March 2021. URL https://cacm.acm.org/magazines/2021/3/250710-the-decline-of-computers-as-a-general-purpose-technology/fulltext. [Online; accessed 11. Jul. 2022]. 9.2.2

[159] CP Neo and VK Varadan. Design and development of electromagnetic absorbers with carbon fiber composites and matching dielectric layers. *Smart materials and structures*, 10(5):1107, 2001. 2.4.1

[160] Ryuma Niiyama, Daniela Rus, and Sangbae Kim. Pouch motors: Printable/inflatable soft actuators for robotics. In *Robotics and Automation (ICRA), 2014 IEEE International Conference on*, pages 6332–6337. IEEE, 2014. 6.2

[161] Aditya Shekhar Nittala, Anusha Withana, Narjes Pourjafarian, and Jürgen Steimle. Multi-touch skin: A thin and flexible multi-touch sensor for on-skin input. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, pages 1–12, 2018. 2.4.1

[162] Anders Q. Nyrud and Tina Bringslimark. Is Interior Wood use Psychologically Beneficial? A Review of Psychological Responses Toward Wood. *Wood Fiber Sci.*, pages 202–218, April 2010. ISSN 0735-6161. URL https://wfs.swst.org/index.php/wfs/article/view/1365. 7.1

[163] Simon Olberding, Nan-Wei Gong, John Tiab, Joseph A Paradiso, and Jürgen Steimle. A cuttable multi-touch sensor. In *Proceedings of the 26th annual ACM symposium on User interface software and technology*, pages 245–254, 2013. 2.4.1

[164] Simon Olberding, Michael Wessely, and Jürgen Steimle. Printscreen: fabricating highly customizable thin-film touch-displays. In *Proceedings of the 27th annual ACM symposium on User interface software and technology*, pages 281–290. ACM, 2014. 2.4.1

[165] Simon Olberding, Sergio Soto Ortega, Klaus Hildebrandt, and Jürgen Steimle. Foldio: Digital fabrication of interactive and shape-changing objects with foldable printed electronics. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*, pages 223–232, 2015. 2.4.1

[166] Kas Oosterhuis and Nimish Biloria. Interactions with proactive architectural spaces: the muscle projects. *Commun. ACM*, 51(6):70–78, Jun 2008. ISSN 0001-0782. doi: 10.1145/1349026.1349041. 2.4.2

[167] Jifei Ou, Lining Yao, Daniel Tauber, Jürgen Steimle, Ryuma Niiyama, and Hiroshi Ishii. *jamSheets: thin interfaces with tunable stiffness enabled by layer jamming*. Association for Computing Machinery, New York, NY, USA, Feb 2014. ISBN 978-1-45032635-3. doi: 10.1145/2540930.2540971. 2.4.2

[168] Jifei Ou, Gershon Dublon, Chin-Yi Cheng, Felix Heibeck, Karl Willis, and Hiroshi Ishii. Cilllia: 3d printed micro-pillar structures for surface texture, actuation and sensing. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pages 5753–5764. ACM, 2016. 2.4.2

[169] Jifei Ou, Mélina Skouras, Nikolaos Vlavianos, Felix Heibeck, Chin-Yi Cheng, Jannik Peters, and Hiroshi Ishii. *aeroMorph - Heat-sealing Inflatable Shape-change Materials for Interaction Design*. Association for Computing Machinery, New York, NY, USA, Oct 2016. ISBN 978-1-45034189-9. doi: 10.1145/2984511.2984520. 2.4.2

[170] Jifei Ou, Mélina Skouras, Nikolaos Vlavianos, Felix Heibeck, Chin-Yi Cheng, Jannik Peters, and Hiroshi Ishii. aeromorph-heat-sealing inflatable shape-change materials for interaction design. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*, pages 121–132. ACM, 2016. 2.4.1, 6.6

[171] Shijia Pan, Ceferino Gabriel Ramirez, Mostafa Mirshekari, Jonathon Fagert, Albert Jin Chung, Chih Chi Hu, John Paul Shen, Hae Young Noh, and Pei Zhang. Surfacevibe: Vibration-based tap & swipe tracking on ubiquitous surfaces. In *Proceedings of the 16th ACM/IEEE International Conference on Information Processing in Sensor Networks*, IPSN '17, pages 197–208, New York, NY, USA, 2017. ACM. ISBN 978-1-4503-4890-4. doi: 10.1145/3055031.3055077. URL http://doi.acm.org/10.1145/3055031.3055077. 2.2.3, 4.6.1

[172] Joseph A Paradiso, Kai-yuh Hsiao, Joshua Strickon, Joshua Lifton, and Ari Adler. Sensor systems for interactive surfaces. *IBM Systems Journal*, 39(3):892–914, 2000. 2.2.3

[173] Joseph A Paradiso, Che King Leo, Nisha Checka, and Kaijen Hsiao. Passive acoustic sensing for tracking knocks atop large interactive displays. In *Sensors, 2002. Proceedings of IEEE*, volume 1, pages 521–527. IEEE, 2002. 2.2.3

[174] John Parkin and Nicola Smithies. Accounting for the needs of blind and visually impaired people in public realm design. *Journal of urban design*, 17(1):135–149, 2012. 8.1

[175] Shwetak N. Patel, Thomas Robertson, Julie A. Kientz, Matthew S. Reynolds, and Gregory D. Abowd. At the flick of a switch: Detecting and classifying unique electrical events on the residential power line. In *Proceedings of the 9th International Conference on Ubiquitous Computing*, UbiComp '07, pages 271–288, Berlin, Heidelberg, 2007. Springer-Verlag. ISBN 978-3-540-74852-6. URL http://dl.acm.org/citation.cfm?id=1771592.1771608. 2.2.3

[176] Shwetak N. Patel, Matthew S. Reynolds, and Gregory D. Abowd. Detecting human movement by differential air pressure sensing in hvac system ductwork: An exploration in infrastructure mediated sensing. In *Proceedings of the 6th International Conference on Pervasive Computing*, Pervasive '08, pages 1–18, Berlin, Heidelberg, 2008. Springer-Verlag. ISBN 978-3-540-79575-9. doi: 10.1007/978-3-540-79576-6_1. URL http://dx.doi.org/10.1007/978-3-540-79576-6_1. 2.2.3

[177] *ICP Impact Hammer*. PCB Piezotronics, 2015. 4.5.1

[178] Matthai Philipose, Joshua R Smith, Bing Jiang, Alexander Mamishev, Sumit Roy, and Kishore Sundara-Rajan. Battery-free wireless identification and sensing. *IEEE Pervasive computing*, 4(1):37–45, 2005. 2.3.1

[179] Ethel Baraona Pohl. In progress: 0-14 tower by Reiser + Umemoto. *ArchDaily*, Sep 2017. URL https://www.archdaily.com/22200/in-progress-0-14-tower-by-reiser-umemoto. 2.1.2

[180] Mariana Popescu, Matthias Rippmann, Tom Van Mele, and Philippe Block. Complex concrete casting: Knitting stay-in-place fabric formwork. In *Proceedings of IASS Annual Symposia*, volume 2016, pages 1–9. International Association for Shell and Spatial Structures (IASS), 2016. 2.1.2

[181] Ronald Poppe. A survey on vision-based human action recognition. *Image and vision computing*, 28(6):976–990, 2010. 2.2.1

[182] Jeffrey D Poston, R Michael Buehrer, and Pablo A Tarazaga. A framework for occupancy tracking in a building via structural dynamics sensing of footstep vibrations. *Frontiers in Built Environment*, 3:65, 2017. 2.2.3

[183] Ivan Poupyrev, Nan-Wei Gong, Shiho Fukuhara, Mustafa Emre Karagozler, Carsten Schwesig, and Karen E Robinson. Project jacquard: interactive digital textiles at scale. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pages 4216–4227. ACM, 2016. 2.4.1

[184] Cheng Qi, Francesco Amato, Mohammad Alhassoun, and Gregory D Durgin. Breaking the range limit of rfid localization: Phase-based positioning with tunneling tags. In *2019 IEEE International Conference on RFID (RFID)*, pages 1–8. IEEE, 2019. 2.3.2

[185] Jie Qi and Leah Buechley. Electronic popables: exploring paper-based computing through an interactive pop-up book. In *Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction*, pages 121–128, 2010. 2.4.1

[186] Mostafa Rahimnejad, Arash Adhami, Soheil Darvari, Alireza Zirepour, and Sang-Eun Oh. Microbial fuel cell as new technology for bioelectricity generation: A review. *Alexandria Engineering Journal*, 54(3):745–756, 2015. 9.2.3

[187] Pavani K Ram, Amal K Halder, Stewart P Granger, Therese Jones, Peter Hall, David Hitchcock, Richard Wright, Benjamin Nygren, M Sirajul Islam, John W Molyneaux, et al. Is structured observation a valid technique to measure handwashing behavior? use of acceleration sensors embedded in soap to assess reactivity to structured observation. *The American journal of tropical medicine and hygiene*, 83(5):1070–1076, 2010. 2.2.2

[188] Raf Ramakers, Kashyap Todi, and Kris Luyten. Paperpulse: an integrated approach for embedding electronics in paper designs. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, pages 2457–

2466. ACM, 2015. 2.4.1

[189] Vaishnavi Ranganathan, Sidhant Gupta, Jonathan Lester, Joshua R Smith, and Desney Tan. Rf bandaid: A fully-analog and passive wireless interface for wearable sensors. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, 2(2):1–21, 2018. 2.3.2

[190] Amos Rapoport. *The meaning of the built environment: A nonverbal communication approach*. University of Arizona Press, 1990. 8.2.2

[191] Majken K Rasmussen, Esben W Pedersen, Marianne G Petersen, and Kasper Hornbæk. Shape-changing interfaces: a review of the design space and open research questions. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 735–744, 2012. 6.1

[192] Nishkam Ravi, Nikhil Dandekar, Preetham Mysore, and Michael L Littman. Activity recognition from accelerometer data. In *Aaai*, volume 5, pages 1541–1546, 2005. 4.7.1

[193] Yili Ren, Sheng Tan, Linghan Zhang, Zi Wang, Zhi Wang, and Jie Yang. Liquid Level Sensing Using Commodity WiFi in a Smart Home Environment. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.*, 4(1):1–30, Mar 2020. ISSN 2474-9567. doi: 10.1145/3380996. 2.3.3

[194] Bruce Richardson, Krispin Leydon, Mikael Fernstrom, and Joseph A Paradiso. Z-tiles: building blocks for modular, pressure-sensing floorspaces. In *CHI'04 extended abstracts on Human factors in computing systems*, pages 1529–1532, 2004. 2.2.3

[195] Elliot J Riley, Erik H Lenzing, and Ram M Narayanan. Characterization of carbon fiber composite materials for rf applications. In *Radar Sensor Technology XVIII*, volume 9077, page 907704. International Society for Optics and Photonics, 2014. 2.4.1

[196] Graham Robinson and J Bruce C Davies. Continuum robots-a state of the art. In *Robotics and Automation, 1999. Proceedings. 1999 IEEE International Conference on*, volume 4, pages 2849–2854. IEEE, 1999. 6.2, 6.4, 6.4.2

[197] Marcus Rohrbach, Sikandar Amin, Mykhaylo Andriluka, and Bernt Schiele. A database for fine grained activity detection of cooking activities. In *2012 IEEE Conference on Computer Vision and Pattern Recognition*, pages 1194–1201. IEEE, 2012. 2.2.1

[198] Timm Rosburg. Tactile ground surface indicators in public places. In *Human Haptic Perception: Basics and Applications*, pages 491–499. Springer, 2008. 8.1

[199] Analisa Russo, Bok Yeop Ahn, Jacob J Adams, Eric B Duoss, Jennifer T Bernhard, and Jennifer A Lewis. Pen-on-paper flexible electronics. *Advanced materials*, 23 (30):3426–3430, 2011. 2.4.1

[200] Alanson P. Sample, Daniel J. Yeager, Pauline S. Powledge, Alexander V. Mami-

shev, and Joshua R. Smith. Design of an RFID-Based Battery-Free Programmable Sensing Platform. *IEEE Trans. Instrum. Meas.*, 57(11):2608–2615, Jun 2008. ISSN 1557-9662. doi: 10.1109/TIM.2008.925019. 2.3.1

[201] Timothy Sandy, Markus Giftthaler, Kathrin Dörfler, Matthias Kohler, and Jonas Buchli. Autonomous repositioning and localization of an in situ fabricator. In *2016 IEEE International Conference on Robotics and Automation (ICRA)*, pages 2852–2858. IEEE, 2016. 2.1.2

[202] Harpreet Sareen, Udayan Umapathi, Patrick Shin, Yasuaki Kakehi, Jifei Ou, Hiroshi Ishii, and Pattie Maes. Printflatables: printing human-scale, functional and dynamic inflatable objects. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, pages 3669–3680. ACM, 2017. 2.1.4, 6.6

[203] Valkyrie Savage, Xiaohan Zhang, and Björn Hartmann. Midas: fabricating custom capacitive touch sensors to prototype interactive objects. In *Proceedings of the 25th annual ACM symposium on User interface software and technology*, pages 579–588. ACM, 2012. 2.4.1

[204] Martin Schmitz, Mohammadreza Khalilbeigi, Matthias Balwierz, Roman Lissermann, Max Mühlhäuser, and Jürgen Steimle. Capricate: A fabrication pipeline to design and 3d print capacitive touch sensors for interactive objects. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*, pages 253–258. ACM, 2015. 2.4.1

[205] Hamza Shaban. Airbnb refunds guest who found indoor cameras during his family's stay. *Washington Post*, Jan 2019. ISSN 0190-8286. URL https://www.washingtonpost.com/technology/2019/01/17/airbnb-refunds-guest-who-found-indoor-cameras-during-his-familys-stay. 2.2.1

[206] John M Shalf and Robert Leland. Computing beyond moore's law. *Computer*, 48 (12):14–23, 2015. 1.1

[207] Ali Sharif Razavian, Hossein Azizpour, Josephine Sullivan, and Stefan Carlsson. Cnn features off-the-shelf: an astounding baseline for recognition. In *Proceedings of the IEEE conference on computer vision and pattern recognition workshops*, pages 806–813, 2014. 2.2.1

[208] Robert F Shepherd, Filip Ilievski, Wonjae Choi, Stephen A Morin, Adam A Stokes, Aaron D Mazzeo, Xin Chen, Michael Wang, and George M Whitesides. Multigait soft robot. *Proceedings of the national academy of sciences*, 108(51):20400–20403, 2011. 6.2, 6.4.3

[209] Jae Mun Sim, Yonnim Lee, and Ohbyung Kwon. Acoustic sensor based recognition of human activity in everyday life for smart home services. *International Journal of Distributed Sensor Networks*, 11(9):679123, 2015. 2.2.2

[210] Joshua R Smith, Kenneth P Fishkin, Bing Jiang, Alexander Mamishev, Matthai Philipose, Adam D Rea, Sumit Roy, and Kishore Sundara-Rajan. Rfid-based techniques for human-activity detection. *Communications of the ACM*, 48(9):39–44,

2005. 2.3.1

[211] Nancy A. Soliman, Nicolas Chanut, Vincent Deman, Zoe Lallas, and Franz-Josef Ulm. Electric energy dissipation and electric tortuosity in electron conductive cement-based materials. *Phys. Rev. Mater.*, 4(12):125401, Dec 2020. ISSN 2475-9953. doi: 10.1103/PhysRevMaterials.4.125401. 2.4.1

[212] Robert F Stinson and Joseph A Sarro. The use of carbon fiber composites in sliding contacts. In *Electrical Contacts, 2002. Proceedings of the Forty-Eighth IEEE Holm Conference on*, pages 175–183. IEEE, 2002. 2.4.1

[213] Emma Strubell, Ananya Ganesh, and Andrew McCallum. Energy and policy considerations for deep learning in nlp. *arXiv preprint arXiv:1906.02243*, 2019. 9.2.2

[214] Erich P. Stuntebeck, Shwetak N. Patel, Thomas Robertson, Matthew S. Reynolds, and Gregory D. Abowd. Wideband powerline positioning for indoor localization. In *Proceedings of the 10th International Conference on Ubiquitous Computing*, UbiComp '08, pages 94–103, New York, NY, USA, 2008. ACM. ISBN 978-1-60558-136-1. doi: 10.1145/1409635.1409649. URL http://doi.acm.org/10.1145/1409635.1409649. 2.2.3

[215] Saiganesh Swaminathan, Kadri Bugra Ozutemiz, Carmel Majidi, and Scott E. Hudson. *FiberWire: Embedding Electronic Function into 3D Printed Mechanically Strong, Lightweight Carbon Fiber Composite Objects*. Association for Computing Machinery, New York, NY, USA, May 2019. ISBN 978-1-45035970-2. doi: 10.1145/3290605.3300797. 3.2, 3.3

[216] Saiganesh Swaminathan, Kadri Bugra Ozutemiz, Carmel Majidi, and Scott E. Hudson. Fiberwire: Embedding electronic function into 3d printed mechanically strong, lightweight carbon fiber composite objects. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, CHI '19, pages 567:1–567:11, New York, NY, USA, 2019. ACM. ISBN 978-1-4503-5970-2. doi: 10.1145/3290605.3300797. URL http://doi.acm.org/10.1145/3290605.3300797. 3.1, 4.1

[217] Saiganesh Swaminathan, Michael Rivera, Runchang Kang, Zheng Luo, Kadri Bugra Ozutemiz, and Scott E. Hudson. Input, Output and Construction Methods for Custom Fabrication of Room-Scale Deployable Pneumatic Structures. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.*, 3(2):1–17, Jun 2019. ISSN 2474-9567. doi: 10.1145/3328933. 3.1, 3.2, 3.3

[218] Saiganesh Swaminathan, Jonathon Fagert, Michael Rivera, Andrew Cao, Gierad Laput, Hae Young Noh, and Scott E. Hudson. OptiStructures: Fabrication of Room-Scale Interactive Structures with Embedded Fiber Bragg Grating Optical Sensors and Displays. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.*, 4(2):1–21, Jun 2020. ISSN 2474-9567. doi: 10.1145/3397310. 3.1, 3.2, 3.3

[219] Saiganesh Swaminathan, Yellina Yim, Scott Hudson, Cynthia Bennett, and Patrick Carrington. From tactile to navtile: Opportunities and challenges with multimodal feedback for guiding surfaces during non-visual navigation. In *Proceed-*

ings of the SIGCHI Conference on Human Factors in Computing Systems, 2021. 3.3

[220] S Takeda, Y Aoki, T Ishikawa, N Takeda, and H Kikukawa. Structural health monitoring of composite wing structure during durability test. *Composite structures*, 79(1):133–139, 2007. 2.4.1

[221] Vamsi Talla, Mehrdad Hessar, Bryce Kellogg, Ali Najafi, Joshua R Smith, and Shyamnath Gollakota. Lora backscatter: Enabling the vision of ubiquitous connectivity. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, 1(3):1–24, 2017. 2.3.2

[222] Vamsi Talla, Bryce Kellogg, Shyamnath Gollakota, and Joshua R Smith. Battery-free cellphone. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, 1(2):1–20, 2017. 2.3.2

[223] Sheng Tan, Linghan Zhang, Zi Wang, and Jie Yang. *MultiTrack: Multi-User Tracking and Activity Recognition Using Commodity WiFi*. Association for Computing Machinery, New York, NY, USA, May 2019. ISBN 978-1-45035970-2. doi: 10.1145/3290605.3300766. 2.3.3

[224] Emmanuel Munguia Tapia, Stephen S Intille, and Kent Larson. Activity recognition in the home using simple and ubiquitous sensors. In *International conference on pervasive computing*, pages 158–175. Springer, 2004. 2.2.2

[225] Shan-Yuan Teng, Cheng-Lung Lin, Chi-huan Chiang, Tzu-Sheng Kuo, Liwei Chan, Da-Yuan Huang, and Bing-Yu Chen. *TilePoP: Tile-type Pop-up Prop for Virtual Reality*. Association for Computing Machinery, New York, NY, USA, Oct 2019. ISBN 978-1-45036816-2. doi: 10.1145/3332165.3347958. 2.4.2

[226] Aud Tennøy, Kjersti Visnes Øksenholt, Nils Fearnley, and Bryan Matthews. Standards for usable and safe environments for sight impaired. In *Proceedings of the Institution of Civil Engineers-Municipal Engineer*, volume 168, pages 24–31. Thomas Telford Ltd, 2015. 8.1

[227] Anja Thieme, Cynthia L Bennett, Cecily Morrison, Edward Cutrell, and Alex S Taylor. " i can do everything but see!"–how people with vision impairments negotiate their abilities in social contexts. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, pages 1–14, 2018. 8.2.2, 8.3.6, 8.5.2

[228] PM Toet, RAJ Hagen, HC Hakkesteegt, J Lugtenburg, and MP Maniscalco. Miniature and low cost fiber bragg grating interrogator for structural monitoring in nano-satellites. In *International Conference on Space Optics—ICSO 2014*, volume 10563, page 105631E. International Society for Optics and Photonics, 2017. 4.3.2

[229] Tatiana Tommasi, Novi Patricia, Barbara Caputo, and Tinne Tuytelaars. A deeper look at dataset bias. In *Domain adaptation in computer vision applications*, pages 37–55. Springer, 2017. 2.2.1

[230] John R Tumbleston, David Shirvanyants, Nikita Ermoshkin, Rima Janusziewicz,

Ashley R Johnson, David Kelly, Kai Chen, Robert Pinschmidt, Jason P Rolland, Alexander Ermoshkin, et al. Continuous liquid interface production of 3d objects. *Science*, 347(6228):1349–1352, 2015. 2.1.1

[231] Stanford University. New Stanford manufacturing process could yield better solar cells, faster chips. *Stanford News*, Mar 2015. URL https://news.stanford.edu/2015/03/24/chips-laser-lift-032415. 3.2

[232] Nirzaree Vadgama and Jürgen Steimle. Flexy: Shape-customizable, single-layer, inkjet printable patterns for 1d and 2d flex sensing. In *Proceedings of the Eleventh International Conference on Tangible, Embedded, and Embodied Interaction*, pages 153–162, 2017. 1.2.5, 2.4.1

[233] Anna Vallgårda. *The dress room: responsive spaces and embodied interaction*. Association for Computing Machinery, New York, NY, USA, Oct 2014. ISBN 978-1-45032542-4. doi: 10.1145/2639189.2639254. 2.4.2

[234] Baptist Vandersmissen, Nicolas Knudde, Azarakhsh Jalalvand, Ivo Couckuyt, André Bourdoux, Wesley De Neve, and Tom Dhaene. Indoor Person Identification Using a Low-Power FMCW Radar. *IEEE Trans. Geosci. Remote Sens.*, 56(7):3941–3952, Apr 2018. doi: 10.1109/TGRS.2018.2816812. 2.3.3

[235] Ambuj Varshney, Andreas Soleiman, and Thiemo Voigt. Tunnelscatter: Low power communication for sensor tags using tunnel diodes. In *The 25th Annual International Conference on Mobile Computing and Networking*, pages 1–17, 2019. 2.3.2, 2.3.3

[236] Tatyana Vasilevitsky and Amit Zoran. Steel-sense: Integrating machine elements with sensors by additive manufacturing. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pages 5731–5742. ACM, 2016. 2.4.1

[237] Anita Vogl, Patrick Parzer, Teo Babic, Joanne Leong, Alex Olwal, and Michael Haller. Stretcheband: Enabling fabric-based interactions through rapid fabrication of textile stretch sensors. In *CHI*, pages 2617–2627, 2017. 2.4.1

[238] Guanyun Wang, Tingyu Cheng, Youngwook Do, Humphrey Yang, Ye Tao, Jianzhe Gu, Byoungkwon An, and Lining Yao. *Printed Paper Actuator: A Low-cost Reversible Actuation and Sensing Method for Shape Changing Interfaces*. Association for Computing Machinery, New York, NY, USA, Apr 2018. ISBN 978-1-45035620-6. doi: 10.1145/3173574.3174143. 2.4.2

[239] Guanyun Wang, Tingyu Cheng, Youngwook Do, Humphrey Yang, Ye Tao, Jianzhe Gu, Byoungkwon An, and Lining Yao. Printed paper actuator: A low-cost reversible actuation and sensing method for shape changing interfaces. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, pages 1–12, 2018. 2.4.1

[240] Hao Wang, Daqing Zhang, Junyi Ma, Yasha Wang, Yuxiang Wang, Dan Wu, Tao Gu, and Bing Xie. *Human respiration detection with commodity wifi devices: do*

user location and body orientation matter? Association for Computing Machinery, New York, NY, USA, Sep 2016. ISBN 978-1-45034461-6. doi: 10.1145/2971648.2971744. 2.3.3

[241] Hongmin Wang, Yifan Diao, Yang Lu, Haoru Yang, Qingjun Zhou, Kenneth Chrulski, and Julio M. D'Arcy. Energy storing bricks for stationary PEDOT supercapacitors. *Nat. Commun.*, 11(3882):1–9, August 2020. ISSN 2041-1723. doi: 10.1038/s41467-020-17708-1. 9.2.1

[242] Jue Wang and Dina Katabi. Dude, where's my card? RFID positioning that works with multipath and non-line of sight. *Proceedings. of the ACM SIGCOMM 2013 conference on SIGCOMM*, 43(4):51–62, Aug 2013. ISSN 0146-4833. doi: 10.1145/2486001.2486029. 2.3.3

[243] Wen Wang, Lining Yao, Teng Zhang, Chin-Yi Cheng, Daniel Levine, and Hiroshi Ishii. *Transformative Appetite: Shape-Changing Food Transforms from 2D to 3D by Water Interaction through Cooking*. Association for Computing Machinery, New York, NY, USA, May 2017. ISBN 978-1-45034655-9. doi: 10.1145/3025453.3026019. 2.4.2

[244] Zeyu Wang, Klint Qinami, Ioannis Christos Karakozis, Kyle Genova, Prem Nair, Kenji Hata, and Olga Russakovsky. Towards fairness in visual recognition: Effective strategies for bias mitigation. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*, pages 8919–8928, 2020. 2.2.1

[245] Martin Weigel, Tong Lu, Gilles Bailly, Antti Oulasvirta, Carmel Majidi, and Jürgen Steimle. Iskin: flexible, stretchable and visually customizable on-body touch sensors for mobile computing. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, pages 2991–3000, 2015. 2.4.1

[246] Martin Weigel, Aditya Shekhar Nittala, Alex Olwal, and Jürgen Steimle. Skinmarks: Enabling interactions on body landmarks using conformal skin electronics. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, pages 3095–3105, 2017. 2.4.1

[247] Mark Weiser. The computer for the 21 st century. *Scientific American*, 265(3):94–105, 1991. ISSN 00368733, 19467087. URL http://www.jstor.org/stable/24938718. 1.1

[248] Michael Wessely, Theophanis Tsandilas, and Wendy E Mackay. Stretchis: Fabricating highly stretchable user interfaces. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*, pages 697–704, 2016. 2.4.1

[249] Michael Wessely, Ticha Sethapakdi, Carlos Castillo, Jackson C Snowden, Ollie Hanton, Isabel PS Qamar, Mike Fraser, Anne Roudaut, and Stefanie Mueller. Sprayable user interfaces: Prototyping large-scale interactive surfaces with sensors and displays. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, pages 1–12, 2020. 2.4.1

[250] Daniel Wigdor et al. Printem: Instant printed circuit boards with standard office printers & inks. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*, pages 243–251. ACM, 2015. 2.4.1

[251] Michele A Williams, Amy Hurst, and Shaun K Kane. " pray before you step out" describing personal and situational blind navigation behaviors. In *Proceedings of the 15th International ACM SIGACCESS Conference on Computers and Accessibility*, pages 1–8, 2013. 8.2.2, 8.5.2

[252] Michele A Williams, Caroline Galbraith, Shaun K Kane, and Amy Hurst. " just let the cane hit it" how the blind and sighted see navigation differently. In *Proceedings of the 16th international ACM SIGACCESS conference on Computers & accessibility*, pages 217–224, 2014. 8.1

[253] Karl Willis, Eric Brockmeyer, Scott Hudson, and Ivan Poupyrev. Printed optics: 3d printing of embedded optical elements for interactive devices. In *Proceedings of the 25th Annual ACM Symposium on User Interface Software and Technology*, UIST '12, pages 589–598, New York, NY, USA, 2012. ACM. ISBN 978-1-4503-1580-7. doi: 10.1145/2380116.2380190. URL http://doi.acm.org/10.1145/2380116.2380190. 4.1

[254] Anusha Withana, Daniel Groeger, and Jürgen Steimle. Tacttoo: A thin and feel-through tattoo for on-skin tactile output. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*, pages 365–378, 2018. 2.4.1

[255] Jacob O Wobbrock, Meredith Ringel Morris, and Andrew D Wilson. User-defined gestures for surface computing. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 1083–1092. ACM, 2009. 6.7.2

[256] Jason Wu, Chris Harrison, Jeffrey P Bigham, and Gierad Laput. Automated class discovery and one-shot interactions for acoustic activity recognition. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, pages 1–14, 2020. 2.2.2

[257] Junichi Yamaoka, Mustafa Doga Dogan, Katarina Bulovic, Kazuya Saito, Yoshihiro Kawahara, Yasuaki Kakehi, and Stefanie Mueller. Foldtronics: Creating 3d objects with integrated electronics using foldable honeycomb structures. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, pages 1–14, 2019. 2.4.1

[258] Yang Research Group. Beyond silicon based devices: Is GaAs the best alternative? *Medium*, Jul 2020. URL https://medium.com/@yrgnthu/beyond-silicon-based-devices-is-gaas-the-best-alternative-799026437e90. 3.2, 3.2

[259] Lining Yao, Ryuma Niiyama, Jifei Ou, Sean Follmer, Clark Della Silva, and Hiroshi Ishii. *PneUI: pneumatically actuated soft composite materials for shape changing interfaces.* Association for Computing Machinery, New York, NY, USA, Oct 2013. ISBN 978-1-45032268-3. doi: 10.1145/2501988.2502037. 2.4.2

[260] Lining Yao, Ryuma Niiyama, Jifei Ou, Sean Follmer, Clark Della Silva, and Hiroshi Ishii. Pneui: pneumatically actuated soft composite materials for shape changing interfaces. In *Proceedings of the 26th annual ACM symposium on User interface software and technology*, pages 13–22. ACM, 2013. 2.4.1

[261] Lining Yao, Jifei Ou, Chin-Yi Cheng, Helene Steiner, Wen Wang, Guanyun Wang, and Hiroshi Ishii. *bioLogic: Natto Cells as Nanoactuators for Shape Changing Interfaces*. Association for Computing Machinery, New York, NY, USA, Apr 2015. ISBN 978-1-45033145-6. doi: 10.1145/2702123.2702611. 2.4.2

[262] Lining Yao, Jifei Ou, Chin-Yi Cheng, Helene Steiner, Wen Wang, Guanyun Wang, and Hiroshi Ishii. Biologic: natto cells as nanoactuators for shape changing interfaces. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, pages 1–10. ACM, 2015. 2.4.2

[263] Hui-Shyong Yeo, Gergely Flamich, Patrick Schrempf, David Harris-Birtill, and Aaron Quigley. *RadarCat: Radar Categorization for Input & Interaction*. Association for Computing Machinery, New York, NY, USA, Oct 2016. ISBN 978-1-45034189-9. doi: 10.1145/2984511.2984515. 2.3.3

[264] Sang Ho Yoon, Ke Huo, Yunbo Zhang, Guiming Chen, Luis Paredes, Subramanian Chidambaram, and Karthik Ramani. isoft: A customizable soft sensor with real-time continuous contact and stretching sensing. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*, pages 665–678. ACM, 2017. 2.4.1

[265] Hironori Yoshida, Takeo Igarashi, Yusuke Obuchi, Yosuke Takami, Jun Sato, Mika Araki, Masaaki Miki, Kosuke Nagata, Kazuhide Sakai, and Syunsuke Igarashi. Architecture-scale human-assisted additive manufacturing. *ACM Transactions on Graphics (TOG)*, 34(4):88, 2015. 2.1.4

[266] Babak Zareiyan and Behrokh Khoshnevis. Interlayer adhesion and strength of structures in Contour Crafting - Effects of aggregate size, extrusion rate, and layer thickness. *Autom. Constr.*, 81:112–121, Sep 2017. ISSN 0926-5805. doi: 10.1016/j.autcon.2017.06.013. 2.1.1

[267] Zhongwen Zhan, Mattia Cantono, Valey Kamalov, Antonio Mecozzi, Rafael Müller, Shuang Yin, and Jorge C. Castellanos. Optical polarization–based seismic and water wave sensing on transoceanic cables. *Science*, 371(6532):931–936, Feb 2021. ISSN 0036-8075. doi: 10.1126/science.abe6648. 3.2

[268] Dingtian Zhang, Canek Fuentes-Hernandez, Raaghesh Vijayan, Yang Zhang, Yunzhi Li, Jung Wook Park, Yiyang Wang, Yuhui Zhao, Nivedita Arora, Ali Mirzazadeh, et al. Flexible computational photodetectors for self-powered activity sensing. *npj Flexible Electronics*, 6(1):1–8, 2022. 9.2.1, 9.2.2

[269] Fusang Zhang, Daqing Zhang, Jie Xiong, Hao Wang, Kai Niu, Beihong Jin, and Yuxiang Wang. From Fresnel Diffraction Model to Fine-grained Human Respiration Sensing with Commodity Wi-Fi Devices. *Proc. ACM Interact. Mob.*

Wearable Ubiquitous Technol., 2(1):1–23, Mar 2018. ISSN 2474-9567. doi: 10.1145/3191785. 2.3.3

[270] Yang Zhang and Chris Harrison. Pulp nonfiction: Low-cost touch tracking for paper. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, pages 1–11, 2018. 2.4.1

[271] Yang Zhang, Gierad Laput, and Chris Harrison. Vibrosight: Long-range vibrometry for smart environment sensing. In *The 31st Annual ACM Symposium on User Interface Software and Technology*, pages 225–236. ACM, 2018. 2.2.3

[272] Yang Zhang, Chouchang (Jack) Yang, Scott E. Hudson, Chris Harrison, and Alanson Sample. Wall++: Room-scale interactive and context-aware sensing. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, CHI '18, page 1–15, New York, NY, USA, 2018. Association for Computing Machinery. ISBN 9781450356206. doi: 10.1145/3173574.3173847. URL https://doi.org/10.1145/3173574.3173847. 2.4.1

[273] Yang Zhang, Chouchang Jack Yang, Scott E Hudson, Chris Harrison, and Alanson Sample. Wall++: Room-scale interactive and context-aware sensing. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, page 273. ACM, 2018. 2.1.5

[274] Yang Zhang, Chouchang Jack Yang, Scott E Hudson, Chris Harrison, and Alanson Sample. Wall++: Room-scale interactive and context-aware sensing. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, page 273. ACM, 2018. 2.2.3

[275] Yang Zhang, Yasha Iravantchi, Haojian Jin, Swarun Kumar, and Chris Harrison. *Sozu: Self-Powered Radio Tags for Building-Scale Activity Sensing*. Association for Computing Machinery, New York, NY, USA, Oct 2019. ISBN 978-1-45036816-2. doi: 10.1145/3332165.3347952. 2.3.3

[276] Mingmin Zhao, Fadel Adib, and Dina Katabi. Emotion recognition using wireless signals. *Commun. ACM*, 61(9):91–100, Aug 2018. ISSN 0001-0782. doi: 10.1145/3236621. 2.3.3

[277] Zhupeng Zheng and Ying Lei. Structural monitoring techniques for the largest excavation section subsea tunnel: Xiamen xiang’an subsea tunnel. *Journal of Aerospace Engineering*, 30(2):B4016002, 2017. doi: 10.1061/(ASCE)AS.1943-5525.0000594. 4.2

[278] Jesus Zozaya. Voltera: Build hardware faster, 2019. URL https://www.voltera.io/. 4.1