Vibroacoustic Materials

Leveraging Material Vibration to Sense Interaction

by João Henrique Santos Wilbert

B.A., UNI-BH Belo Horizonte University Center (2005)
M.A., Goldsmiths University of London (2008)

Submitted to the Program in Media Arts and Sciences, School of Architecture and Planning, in partial fulfillment of the requirements for the degree of

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Author____
Program in Media Arts and Sciences
August, 14, 2020

Certified by______________________________________
Hiroshi Ishii, Thesis Supervisor
Jerome B. Wiesner Professor of Media Arts and Sciences

Accepted by______________________________________
Tod Machover, Academic Head
Program in Media Arts and Sciences

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Materiality has been a theme of extensive discussion in the field of human-computer-interaction (HCI) in recent years. This perspective has presented new opportunities to reimagine how computing technology can manifest itself in the physical world through materials and objects we use every day. The development of materials with embedded sensing is a crucial requirement for the fulfillment of the ubicomp vision. This thesis proposes to leverage material properties as an inherent capability of a material to afford interactivity. It focuses on how mechanical vibration, a property response that is natural and common to any material, can be leveraged to sense interactions. It presents PaperAware, an example of a vibroacoustic sheet material that can support touch, swipe, and non-contact interactions like blowing on the paper's surface. The thesis concludes by proposing a vision and series of techniques to develop materials with inherent vibroacoustic sensing capability.

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This dissertation/thesis has been reviewed and approved by the following committee members

Advisor____
Hiroshi Ishii
Jerome B. Wiesner Professor of Media Arts and Sciences

Reader____
Joseph Paradiso
Alexander W. Dreyfoos Professor in Media Arts and Sciences

Reader____
Zach Lieberman
Adjunct Associate Professor of Media Arts and Sciences

This thesis is dedicated to my wife Denise & son Yuri.

0.1 Preface

I wrote this thesis in 2020 during challenging times. The COVID19 pandemic, which first seemed to be an isolated event, changed everything everywhere. Until science can find vaccines, the best solution so far is empty the spaces we work, stop socializing, and isolate ourselves from one another. Being healthy is the goal; everything else is surplus.

When I felt most safe and secure, everything turned upside down into unexpected and inexplicable. I left MIT, Cambridge, and the US to Brazil. I took what I could to set up a new lab. I had to improvise and be creative. Do more with less. Focus more on thinking, less on worrying.

I am proud of what I could accomplish and grateful to have so many people by my side.

Figure 1: Photograph of my homelab in Brazil.

0.2 Acknowledgments

Thank you, my friend, collaborator, and mentor Dr. Sanad Bushnaq for the support in all aspects of life and work. Cannot stress enough how good it is working with you.

Thank you Prof. Hiroshi Ishii, for your believing in my work, inviting me to be part of such a special place as TMG, guiding me and offering your kind help and support during challenging times.

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Thank you to my fellow TMG colleagues and alumni: Hila Mor, Joanne Leong, Yun Choi, Taka Yoshida, Jack Forman, Dan Levine, Amos Golan. Thanks, Deema, Paula and Jon for supporting our work and making it possible. Thanks, Ken Nakagaki, for the discussions and for helping me learn how to do research.

Thanks to my friends in ResEnv: Bryan Mayton for helping make my circuits better. Mark Feldmeyer for teaching me what is going under the hood. Don Derek for the music and being an amazing collaborator. Spencer Russel for teaching me about sound research. Irmandy Wicaksono for joining in on fabrication experiments.

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To Media Lab professors and staff: Thank you, Tod Machover, Pattie Maes, Canan Dağdeviren being mentors and friends. Thank you Sarra Shubart and Monica Orta for helping me navigate the Media Lab during choppy waters.

Thank you Dr. Wei Ian letting me to work alongside you on such an amazing technological feat.

Thank you, my readers Prof. Joe Paradiso for inspiring me to get deep into electronics. Thank you, Zach Lieberman, for being my long time friend and role model. You taught me how to make art and not tech.

Thank you, my Cambridge friends Max, Helena, Lola, Rosa, Rica, Fernanda, for the endless laughs and joy when everything was way too serious. Max, I admire your wisdom and wholeheartedness. Thank you to my extended family in Brazil, Luciano, Andrea, Ana Maria and Yasmim for the love and support.

Finally, I would like to thank my loving father, João Carlos and mother Georgina. For raising me the way I am, sparking my curiosity and giving me the love, support and freedom to pursue my dreams. *Vamo que vamo!*

Foremost, thank you to my beloved wife and best friend. I spent the best years of my life with you. Thank you for standing by my side the whole time. My dear son Yuri, your smile gives me the strength to carry on. In the words of Tom Jobim, *não há vocês sem mim e eu não existo sem vocês.*

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Chapter 1

Introduction

"*Machines that fit the human environment, instead of forcing humans to enter theirs, will make using a computer as refreshing as the walk in the woods.*"

— Mark Weiser

1.1 Initial Remarks

The seminal paper The Computer for the 21st Century (Weiser, 1991) has long inspired the field of human-computer-interaction (HCI) to pursue new forms in which computing technology can manifest itself in the physical world.

The Ubiquitous Computing vision proposed by Weiser has set the foundation for several interface paradigms, including Tangible Bits (Ishii and Ullmer, 1997) and Radical Atoms (Ishii et al., 2012), that have demonstrated novel interactions enabled by direct manipulation of materials as a manifestation of digital information. Additionally, these paradigms have shown how computing can manifest in materials and artifacts of everyday life, a concept explored by the material-turn in HCI (Wiberg, 2017).

Beyond the novel interactions enabled by Tangible Bits, Radical Atoms, and the material-turn, new HCI paradigms require the development of novel methods to enable materials to sense interaction with its surroundings.

Researchers (Bosse et al., 2016; Lang et al., 2011) suggest that in order to enhance materials with interactive capability, sensing technology can be integrated into a material through a top-down or bottom-up approach. While the top-down approach seeks to embed an active sensing layer on a material, a bottoms-up approach utilizes intrinsic material properties as sensing enablers, as shown in Figure 1.1.

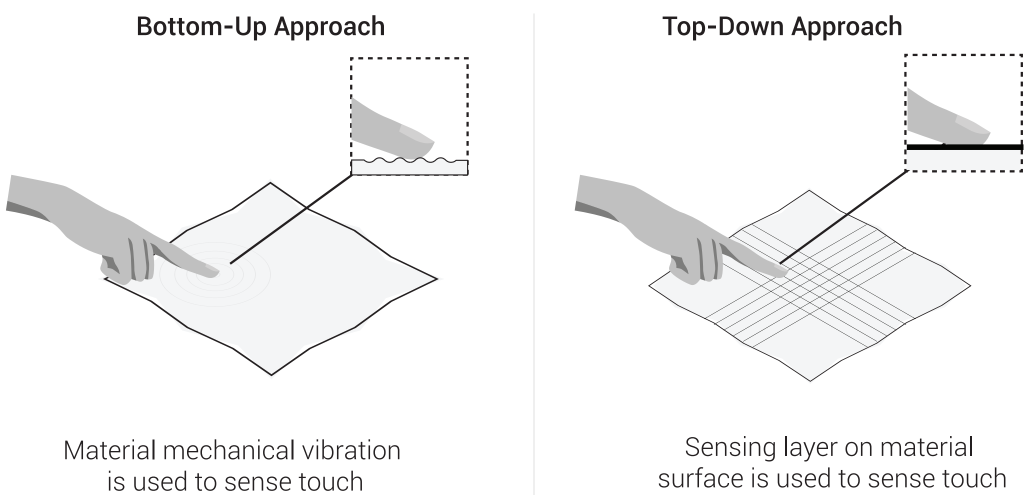


Figure 1.1: Diagram illustrating top-down and bottom-up approach to sensing. *Left:* Sensing touch interaction through mechanical vibration on material surface. *Right:* Sensing touch through a separate active layer applied on top of passive material.

An extensive body of work has demonstrated how materials can sense through a top-down approach, by deeply embedding active sensing layers in materials. In this approach, the material itself serves the only purpose of being a structure or substrate to an active sensing layer. It does not leverage the sensing potential of the material itself.

In contrast, a bottom-up approach seeks to utilize inherent material properties to sense, elevating the material from the condition of a substrate to the one of a multimodal sensor.

The challenge of utilizing a bottom-up approach to sense can be due to the many practical challenges in leveraging properties of materials to sense interaction, alternatively, due to the lack of an integrated framework that demonstrates the use of inherent material properties to sense. In order to enable new modalities for sensing in HCI, this thesis takes a bottom-up approach to sense interaction.

It proposes a strategy for the development of materials with inherent sensing capability. More specifically, a framework to design and fabricate materials that can sense through changes in their optical, magnetic, thermal, electrical, chemical, mechanical properties as a response to external stimuli.

This approach requires the instrumentation of a material with a transducer that can measure the change in a given property response. A challenge further discussed in the thesis.

The thesis focuses on vibration as a material mechanical property response to demonstrate the potential of sensing through material properties. It explores leveraging vibration to sense interaction.

Vibration is a mechanical property response natural and common to any material. Vibrations propagate through the extent of materials even when generated by weak forces. It is a phenomenon that can be accurately measured and exhibits a fast response time-wise. Additionally, if examined in detail, vibration patterns can reveal a rich set of information about the source of vibration.

The thesis demonstrates the benefit of using vibration as an inherent material property to sense interaction through an example implementation of paper as a vibroacoustic material entitled PaperAware. The implementation extends into an exploration of fabrication methods of materials with inherent vibroacoustic sensing capability. Lastly, the thesis concludes with a vision for future applications of vibroacoustic materials in the domain of HCI and beyond.

The perspective of sensing interactions through material properties may lead to the development of novel sensing modalities. Additionally, elevating materials to the status of a sensor may enable new forms and expressions to computing technology, ultimately taking steps closer towards the long term goal of blending technology with everyday life, as envisioned by Mark Weiser.

1.2 Motivations

Previous literature report on different techniques to integrate sensing technology in materials as a pathway towards ubiquitous computing (Gong et al., 2011; Kawahara et al., 2013; Bosse et al., 2016).

For a natural integration between sensors and materials to occur, we must focus our attention on the relationship between materials and technology. More specifically, on the means through which technology is embedded into the material to augment that material with interactive capability.

Despite its potential, bottom-up approaches to sensing have been underexplored in the context of HCI. There is no theoretical framework that leverages material properties for sensing interaction. Furthermore, an in-depth study of a material property a sensing enabling is also lacking.

A bottom-up approach to the integration of technology in materials should: first, take advantage of material properties and structure as a potential for interaction. Second, use technology as a means to unlock a material capability and not neglect it. Third, retain materials', initial aesthetics, and purpose. The integration would then result in a material naturally enhanced with interactive capability.

If we can find a solution that satisfies those requirements, it could enable the exploration of the textural and aesthetic richness of materials to afford interactions while respecting the material's initial purpose. In this way, technology could transparently augment our social and personal environment without getting on the way. It can also enable natural material interactions in our social environment beyond computer screens and keyboards. Ultimately it could enable computation to be transformed and reimagined in new forms and expressions.

This thesis roots its motivations in the challenge of exploring a bottom-up approach to interactivity. More specifically, attempting to unlock the potential that materials hold in their properties to sense interaction.

This perspective can propel the field of HCI forward, as it may lead to novel sensing techniques. Meanwhile, it can re-frame the relationship between materials and technology as a whole.

1.3 Thesis Aims

This thesis postulates that in order for technology to blend with everyday life as envisioned by Mark Weiser, we must seek new ways in which materials and objects can naturally sense the interactions with their surroundings.

The thesis aims to develop a theoretical framework demonstrating how to utilize inherent material properties to sense interactions.

It focuses on one property of a material as an example and presents an in-depth study on how material vibration, a mechanical property response, can be leveraged for sensing.

It presents an implementation of paper as a vibroacoustic material with the goal to demonstrate the possibilities of utilizing material vibration as an inherent sensing enabler in the context of human-computer interaction (HCI).

Lastly, it envisions future scenarios and applications made possible by materials with inherent sensing capability.

1.4 Thesis Contributions

This thesis proposes the following contributions:

1.
A theoretical framework that builds on a bottom-up approach to sensing that explores how materials can sense interaction through their inherent properties.

2.
An in-depth study on the use of material vibration, an inherent mechanical property response, to sense material interactions.

3.
Implementation of paper as vibroacoustic material, including the development of sensors, hardware, software, design space, and applications.

4.
A future vision and series of experiments for the fabrication of materials with inherent vibroacoustic sensing capability.

1.5 Thesis Outline

Chapter 2: The Promise of Ubicomp
This chapter introduces the paradigms of Ubiquitous Computing, Radical Atoms, Tangible Bits as fundamental paradigms for the expression of technology in the physical world. It details top-down and bottom-up approaches to sensing and survey prior work in material interfaces. It concludes by discussing the potential of a bottom-up perspective to sense interactions.

Chapter 3: Material Inherent Sensing
This chapter expands on a bottom-up approach to sensing by presenting a theoretical framework to develop materials with inherent sensing capability. It begins by introducing concepts from material science and sensing technology as base knowledge in devising a strategy to design and develop materials that can sense through their properties.

Chapter 4: Vibroacoustic Materials
This chapter focuses on leveraging vibration, a material mechanical property, as an example of a bottoms-up approach to sensing. It first introduces concepts from vibroacoustics and piezoelectrics as base knowledge for creating material with vibroacoustic sensing capability.

Chapter 5: Paper as a Vibroacoustic Material
This chapter presents the PaperAware project. An example of a bottom-up approach to sensing. It goes in detail on the implementation of paper as vibroacoustic material, including related work, hardware platform, software algorithm, evaluation, design space, application scenarios, and future work.

Chapter 6: The Axis of Disappearance
This chapter extends PaperAware as a project by presenting a series of ex-

periments that further integrate a transducer into sheet material with the ultimate goal of developing a material that can sense through mechanical vibration. It presents the steps taken for fabrication and learnings from the process.

Chapter 7: Vibroacoustic Materials & Beyond
This chapter presents the future vision for a bottom-up approach to sensing. The concepts presented utilize vibroacoustic materials in different applications and future scenarios.

Chapter 8: Conclusion
Lastly, this chapter concludes the thesis with final remarks demonstrating how a bottom-up approach and inherent material sensing can take us closer to Mark Weiser's vision of ubicomp.

Chapter 2

The World as an Interface

"*In a world where practicality and functionality can be taken for granted, the aesthetics of the post-optimal object could provide new experiences of everyday life, new poetic dimensions.*"

— Anthony Dunne and Fiona Raby

2.1 Introduction

This chapter introduces the paradigms of Ubiquitous Computing, Radical Atoms, Tangible Bits as fundamental paradigms for the expression of technology in the physical world. It details top-down and bottom-up approaches to sensing and survey prior work in material interfaces. It concludes by discussing the potential of a bottom-up perspective to sense interactions.

2.2 The Promise of Ubicomp

The vision for Ubiquitous Computing proposed by Mark Weiser at Xerox PARC in 1991 is foundational to human-computer-interaction (HCI) as a field. Ubicomp envisioned that computers manifest as part of everyday life through a constellation of single purposed devices highly embedded in the objects we use and environments we live everyday (Weiser, 1991).

In his view, computing would exist in different forms and sizes (Figure 2.1) connected through a network in which an ambient contextual intelligence would emerge. Ubicomp postulates a view in which computers would become invisible both in form and as a metaphor. "A process of drawing computers out of their electronic shells" (Weiser, 1991).

Figure 2.1: Image of Ubiquitous Computing device prototypes at XEROX Palto Alto Research. *Left:* Prototypes of computer scratch pads *Right:* Researchers at XEROX Palto Alto experimenting with prototypes of boards, pads and tabs. *Source:* Weiser (1991)

The trends of modern technology such as smartphones, tablets, and Internet of Things (IoT) devices have permeated everyday life; we became less aware of them, fulfilling their metaphoric disappearance. When it concerns the form in which technology manifests in everyday life, rather than taking computers out of their shells, the commercial approach in the practice of design of technology considers form as the package to the internal workings of a device (Dunne, 1999). Figure 2.2 represents this in which ubiquitous internet-of-things (IoT) device Amazon Echo is shown taken apart and as a whole. The design expression of Amazon Echo serves the only purpose of an enclosure to its internal components.

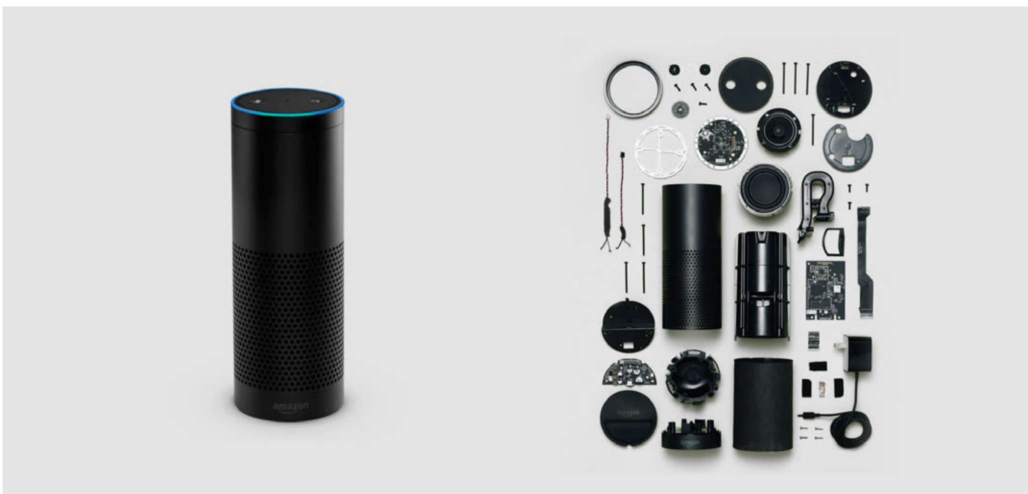


Figure 2.2: Picture that illustrates the commercial approach to design of technology as a package to electronics. *Left:* Amazon Echo Device. *Right:* Amazon Echo taken apart showing the device form as a housing to internal components. *Source:* McLellan (2013)

2.2.1 Tangible Bits

Inspired by the Ubicomp program, the vision proposed by Tangible Bits (Ishii and Ullmer, 1997) breaks with the forms imposed by the commercial approach of technology design. It seeks to explore the tangible richness and the direct manipulation of physical artifacts to reconcile physical experience and the dynamic nature of digital information. Through this exercise, it proposes new metaphors and embodiment to computing. Similarly, it augments physical objects with digital information. Tangible Bits is an attempt to establish new relationships between familiar objects and their electrical properties (Dunne, 1999).

The benefit of this reconciliation is that it maximizes the legibility of the interface. Additionally, it uses the dexterity of human hands as the manipulator of the interface (Ishii and Ullmer, 1997).

Tangible Bits has since founded the paradigm for Tangible User Interfaces (TUI) that transforms artifacts from the physical world into interfaces to digital computation, as shown in Figure 2.3.

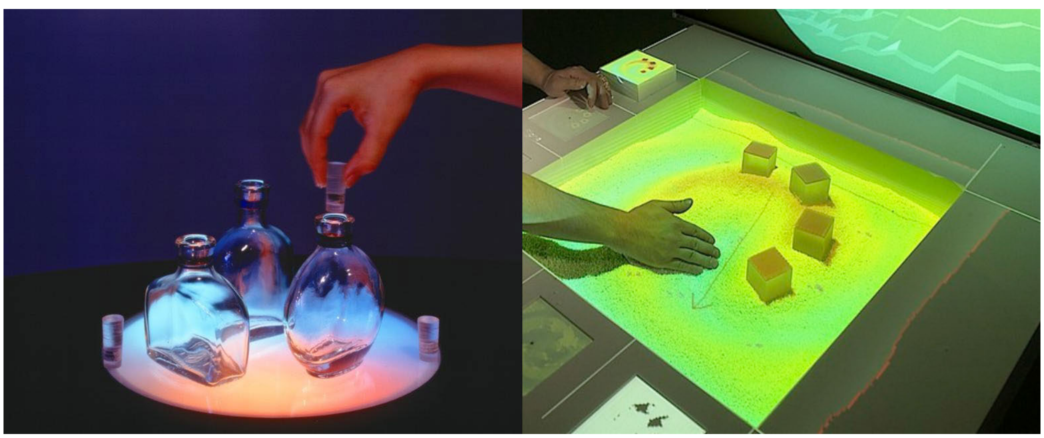


Figure 2.3: Projects that demonstrate the Tangible User Interfaces paradigm. *Left:* musicBottles are used as a metaphor to embody a music player by letting the sound escape a bottle like a scent. *Source:* Ishii et al. (2001) *Right:* SandScape enables the direct manipulation of a 3D digital model by sculpting sand. *Source:* Ishii et al. (2004)

In a Tangible User Interface, interactions with the physical elements affect a digital counterpart. However, changes in the digital state of information cannot flow back into the physical world. The tangible user interface is inherently unidirectional.

The contrast between the dynamic nature of digital information and the static nature of physical matter contrast. As a consequence, physical objects cannot update the form, position, properties as pixels on a screen. This may explain the challenge of making tangible interfaces bi-directional.

2.2.2 Radical Atoms

The Radical Atoms vision proposes a bi-directional entanglement between the physical and digital. It does that by proposing the creation of dynamic, shape-changing materials that can embody digital information in the form of physical matter and update its digital representation with changes from the physical world (Ishii et al., 2012).

Radical Atoms focuses on direct interaction with matter. Perfect Red represents this tight coupling between physical and digital in the form of a hypothetical clay-like material that can update its physical properties with software-like traits (Figure 2.4). Inspired by Computer-Aided Design (CAD) software, by physically manipulating the clay, the dexterous hands of the user can perform Boolean operations on physical matter. These include subtraction, duplication, and other actions only existent in the realm of software. While still a hypothetical material, Perfect Red inspires what programmable matter could be. An entity with the capability of sensing, processing, and outputting information while in the form of clay-like material.

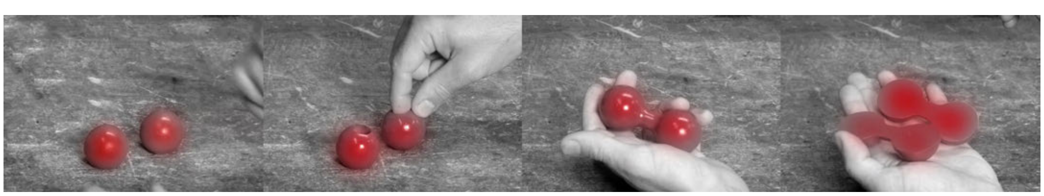


Figure 2.4: Frames extracted from concept video of Perfect Red. The hypothetical digital clay-like material can perform boolean operations such as division, subtraction and addition embodied in physical form. *Source:* Ishii et al. (2012)

From an interaction design perspective, Perfect Red is the ideal radical material. It makes us contemplate the world as a sophisticated palette of materials with the potential of becoming user interfaces. It demonstrates how materials with dynamic properties can afford new interactions by switching states: transparent/opaque, reflective/absorptive, electrically conductive/electrically insulating, thermally conductive/thermally insulating, magnetic/nonmagnetic, flexible/rigid, luminous/non-luminous, elastic/non-elastic, viscous/fluid.

As emphasized by Wiberg (2017), it demonstrates that “computing can take any form, material can be reactivated and reimagined in a computational moment”.

2.2.3 The Material Turn in HCI

Perfect Red is an example that demonstrates how materiality has increasingly become a central theme to HCI in recent years, a concept entitled the material-turn (Wiberg et al., 2013; Jung and Stolterman, 2011; Wiberg, 2017; Robles and Wiberg, 2010; Kwon et al., 2014). This focus regards the manifestation of digital information in the physical world. A material-centric view of HCI elevates the aesthetical and functional richness of materials as the means to provide affordances to computational technology. With the ultimate objective to reconcile the world of bits and atoms (Wiberg et al., 2013). Material-centric HCI shifts the focus from hardware and software to the role of materials in the interaction loop.

Additionally, this seeks to explore how computation can come to expression through integration with other materials by viewing computational technology itself as a material. It then promotes the construction of interfaces that enhance traditional materials such as textiles, wood, clay, paper with computational capability. Vallgårda and Redström (2007) refer to the blending of traditional and computational materials to as the creation of “computational composites".

Thinking of materials and computers as having the same substance "opens up a design space where we can explore new forms, functionalities, and appearances of computing across physical, digital and even immaterial materials" (Wiberg, 2017).

Figure 2.5 shows a collection of artifacts that a person touches every day. A vibrant pattern of material substance (form, color, texture, hardness, softness, flexibility) emerges through the objects in the image. It also shows how computing technology makes up a small, bland portion of the textural richness of all other artifacts from everyday life.

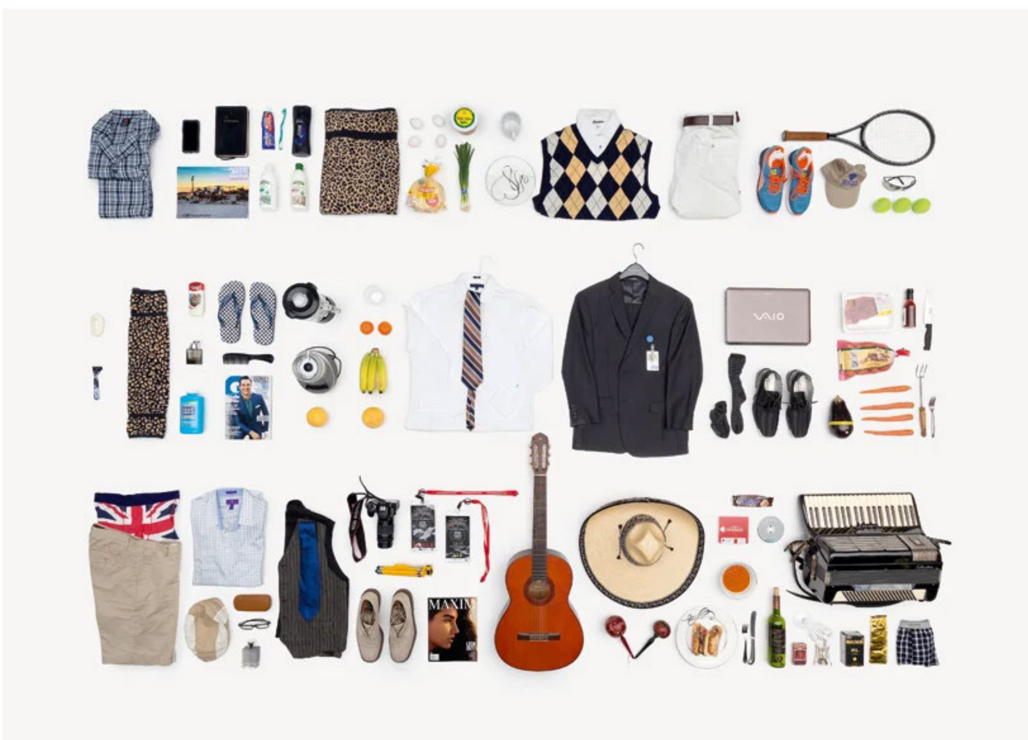


Figure 2.5: Collection of objects that are touched by one person during a 24 hour period. Part of the book Every Thing We Touch: A 24-Hour Inventory of Our Lives. *Source:* Zuccotti (2015)

This material diversity demonstrates the sensorial richness of everyday life. It enables the contemplation of everyday materials and objects as interfaces with a rich set of affordances. Secondly, it demonstrates which familiar objects can embody digital information. Not everything we touch should become a computational interface. Instead, it inspires the means through which computers can be taken out of their shells as initially envisioned by Mark Weiser.

By contemplating the world as an interface, we are exercising a process of technological dematerialization. As mentioned by London based industrial designer Anthonny Dunne: "dematerialization is seen as a way of providing *transparent* interfaces for computers by embedding the technology in familiar objects and environments and introducing a high degree of automation" (see Dunne, 1999, p. 16).

While consumer electronics revolve around interaction with touch screens, voice, and camera-based techniques, a material approach to interaction design promotes the embodiment of computation in the material and social environment. As Dourish (2001) defines "the creation, manipulation, and sharing of meaning through engaged interaction with artifacts" (Dourish, 2001).

2.3 Sensing in Materials

The paradigms explored in Radical Atoms, Tangible Bits, and the material-turn emphasize the importance of the development of methods in which computing can be transparently integrated into materials.

One of the key requirements for a material to afford interactivity is the ability of that material to report information about its surroundings, a capability that can be delivered by embedded sensors.

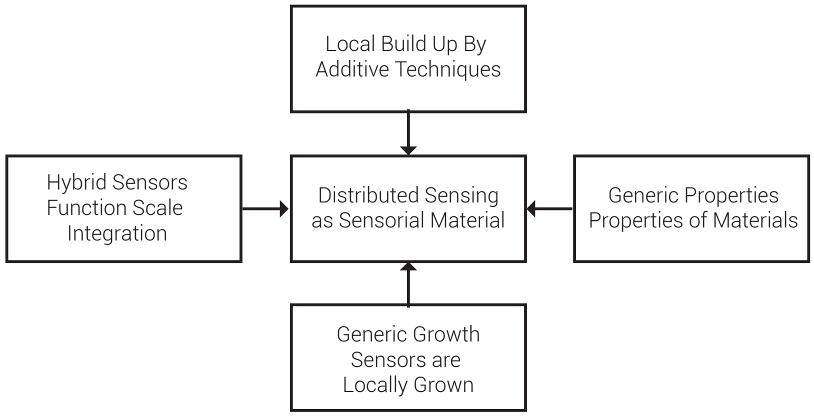


Figure 2.6: Methods for integration of sensor technology in materials proposed by Bosse et al. (2016) .

Bosse et al. (2016) suggest that the integration of sensing technology into a raw material has to take into account multiple factors:

- First, the sensor-material must be able to capture and sample raw data, process, and abstract the data towards higher-level information as part of a decision making process.
- Secondly, the integration method must respect the material properties and appearance. The added functionality must be integrated without compromising the ability of the material to execute its primary task.
- Thirdly, power is a pre-requisite that presents challenges to the mobility of the device and ability self sustain long term periods without maintenance.

Lang et al. (2011) proposes that there are four main approaches to realize ubiquitous computing, as shown in Figure 2.6. A view that advocates for a shift from embedding sensors to development of *sensorial materials*.

Lang proposes a further simplification of these methods by categorizing the techniques to embed material with sensors as a top-down or bottom-up approach, as shown in Figure 2.7 (see Bosse et al., 2016, p.5).

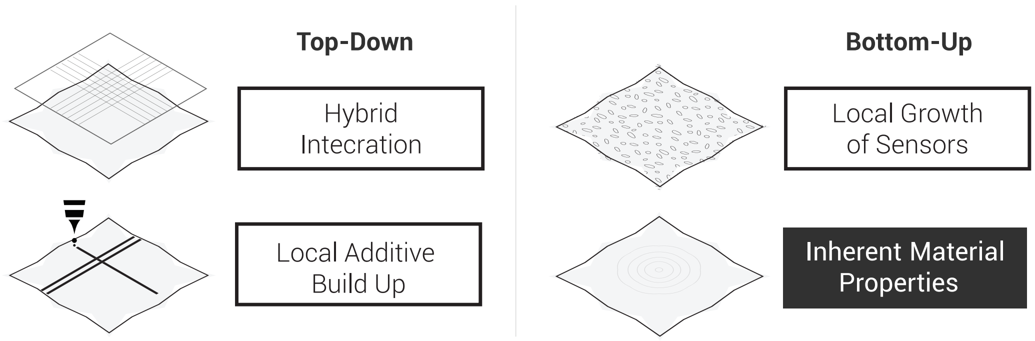


Figure 2.7: Diagram that illustrates top-down and a bottom-up approach (the focus of this thesis) to embed sensing in materials. Lang et al. (2011).

2.3.1 Top-down Approach to Sensing

In a top-down approach, the sensor and material are integrated as a hybrid where the sensor is produced separately and then later integrated into a material through a different process. In this method, the material is used as a structural base for the sensor. It bears no active participation in the sensing technique. The interaction with the material is sensed by an active sensing layer, and the material acts merely as a structural base to the sensor.

An example of a top-down approach is Project Jacquard the textile sensor developed by Google. In Project Jacquard multiple strands of copper thread are intertwined with textile yarn. The copper threads are produced as a separate process and integrated into the yarn. Project Jacquard utilizes capacitive sensing techniques to recognize gestures including discrete, continuous touch and swipes (Poupyrev et al., 2016).

In this example, the capacitive sensing technique makes use of the electrical properties of the copper thread that is intertwined with the textile. The textile yarn itself is only a structural element to the active sensing layer. Figure

2.8 shows copper threads used by Jacquard textile for capacitive sensing integrated with the natural textile yarn resulting in a hybrid of conductive and non-conductive textile.

Figure 2.8: Image of Project Jacquard by Google. *Left:* Close-up of yarn comprised of conductive and non-conductive material. *Right:* Jacquard yarn woven into the cuff of Levis jacket. *Source:* Poupyrev et al. (2016)

The second example of a top-down approach is through the additive build-up of a sensing layer in a base material. In this method, a sensor is applied to the target material *in situ* through the deposition of a sensing layer on a substrate. The material and sensor are produced using the same process. An example of this approach is the utilization of 3D printing to embed strain gauges in highly flexible elastomers (Figure 2.9), as demonstrated by Muth et al. (2014).

In this configuration, change in the mechanical properties of the elastomer is directly affecting the sensor. As the material stretches, the conductive traces from strain gauges are pulled apart, causing the resistance to increase. This implementation is a top-down approach to sensing since no properties of the material itself are being utilized to sense the stretching motion. Rather, as the material deforms, it affects the physical structure of the active sensing layer (the strain gauge) that is being used to measure the change in the material.

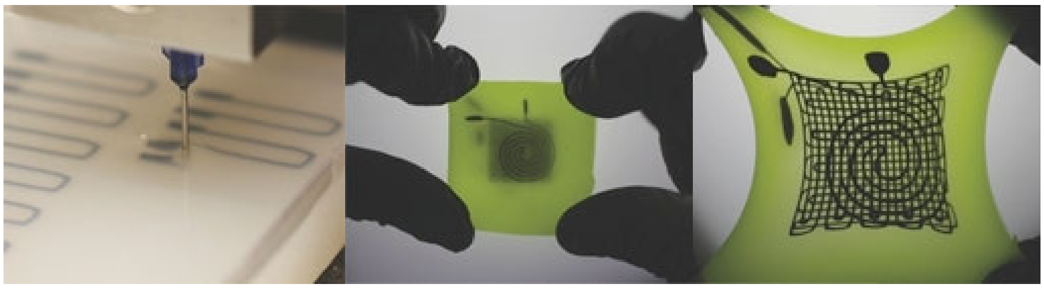


Figure 2.9: Image of elastomers with embedded strain gauges. *Left:* Deposition process for conductive traces. *Middle:* Elastomer with embedded strain gauge at rest position. *Right:* Elastomer with sensor in stretched position. *Source:* Muth et al. (2014)

2.3.2 Survey of Top-down Material Interfaces

A top-down approach to sensing has been the most commonly used technique in HCI. Several examples in the literature demonstrate the augmentation of materials with interactive capability by adding an active sensing layer.

Textiles & Fabric

Textiles are widely explored as interactive interfaces (Figure 2.10). Textile making techniques such as weaving, knitting have also been combined with methods from digital fabrication and electronics. The use of conductive, piezoresistive, piezoelectric yarns, and shape memory alloys enabled the creation of textile-based interactive interfaces (Orth, Smith, Post, Strickon and Cooper, 1998; Orth, Post and Cooper, 1998), energy harvesting apparel (Lund et al., 2018) and actuated textile shutters (Coelho and Maes, 2009). Integration is also successfully demonstrated at the manufacturing scale (Ou et al., 2019; Poupyrev et al., 2016).

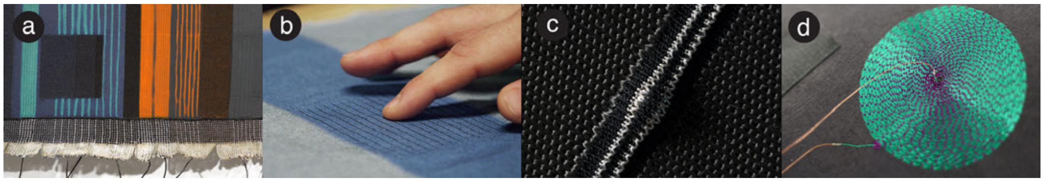


Figure 2.10: Examples of textiles as a material interface. *a.* Color changing electronic textiles (Orth, Post and Cooper, 1998). *b.* Textile gestural input interface (Poupyrev et al., 2016) *c.* Knitted piezo-resistive yarns for sensing (Ou et al., 2019). *d.* Embroidered speaker without permanent magnets (Preindl et al., n.d.).

Paper & Sheet Material

Paper and sheet material have also been explored as input and output surfaces with interactive capability as shown in Figure 2.11. Interactions include: touch tracking (Zhang and Harrison, 2018; Gong et al., 2014*a*; Li et al., 2016), shape awareness (Wessely et al., 2018; Olberding et al., 2013), ability to sense bending and deformation (Rendl et al., 2012), energy generation (Karagozler et al., 2013), actuation (Wang et al., 2018) and visual display (Klamka and Dachselt, 2017; Tsujii et al., 2013). The increased availability of conductive inks compatible with commercially available inkjet printers has also transformed paper into an electronics prototyping platform (Kawahara et al., 2013; Hodges et al., 2014; Qi and Buechley, 2010, 2014; Coelho et al., 2009).

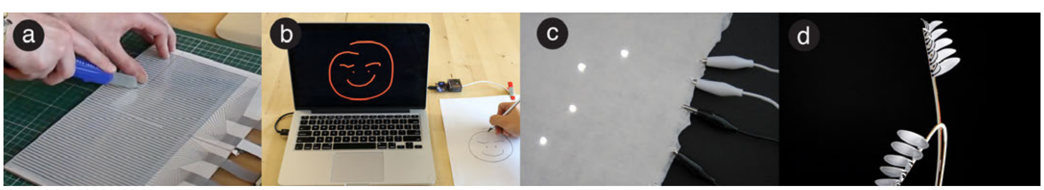


Figure 2.11: Examples of paper as an interactive surface. *a.* Shape aware paper detects cutting patterns (Wessely et al., 2018). *b.* Real time touch tracking on paper (Zhang and Harrison, 2018) *c.* Paper visual displays with led embedded during pulp making process (Coelho et al., 2009). *d.* Paper printed actuators (Wang et al., 2018).

Fur & Hair-Like Structures

Researchers have also demonstrated computational design of material textures with sensing and actuation ability, as shown in Figure 2.12. Different methods have been explored to develop input/output hair-based interfaces through mechanical actuation or use of shape-memory-alloys (Umezu et al., 2014; Raffle et al., 2003; Coelho and Maes, 2008; Nakayasu, 2016) and 3D printing (Ou et al., 2016; Laput, Chen and Harrison, 2015).

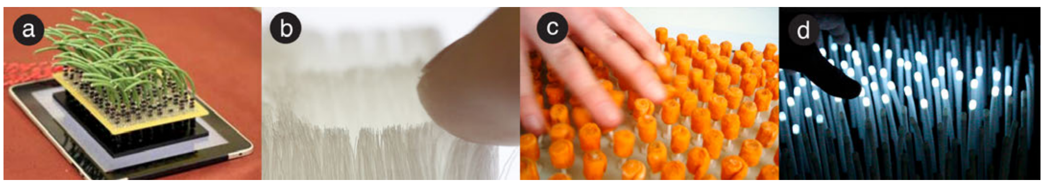


Figure 2.12: Examples of textural interfaces. *a.* Smart hair with shape-memory alloy and light sensor (Umezu et al., 2014). *b.* 3D printed hair with sensing and actuation capability (Ou et al., 2016) *c.* Paper visual displays with led embedded during pulp making process (Raffle et al., 2003). *d.* Motion display build with SMA strands (Nakayasu, 2016).

Paint and Pigments

Diverse materials are enhanced with sensing capability through the use of pigments and inks, as shown in Figure 2.13. Examples include conductive ink (silver nanoparticle), conductive polymer (PEDOT:PSS), thermochromic pigments in and Indium Tin Oxide (ITO).

2.3.3 Bottom-up Approach to Sensing

In a bottom-up approach to sensing, the host material takes an active role to become a sensing enabler through its mechanical, electrical, optical, thermal, and magnetic properties. Changes in any of these properties given external stimuli are the means through which interaction with that material can be sensed. In this scenario, the material itself, not a sensing layer, acts as a sensor through its properties as a response to a source of energy.

Figure 2.13: Examples of interactive inks and pigments. *a.* Interactive drawing with thermochromic ink (Hutton, n.d.). *b.* Conductive coating used for touch sensing on everyday objects (Zhang et al., 2017) *c.* Visual LED display applied on Indium Tin Oxide (ITO) coated on glass. (Adafruit, 2020)

In a bottom-up approach to sensing, the host material must have the means to track the change in a property as it responds to external stimuli. In order for changes to be measured, it requires the integration of a transducer into the material. The transducer acts as an interface between the internal property change and an external measuring device. Section 3.3 further describes this requirement.

A simple scenario can exemplify the use of a material property for sensing: by leveraging changes in the thermal property of a material, it will enable that material to sense touch interaction.

When touching, the hand will transfer thermal energy to the material. The change in material temperature can determine whether the material is touched. By observing the change in temperature across the extent of the material, one can also estimate the touch location. The response time of the system will vary based on the thermal conductivity of the material in question. Hence, specific properties will make better sensing enablers than others for each type of material.

In contrast to a top-down approach, there are only a few examples of research that leverages inherent material properties for sensing, and these examples are mostly outside the domain of HCI.

For instance, inherent material sensing has been explored in structural engineering to monitor and prevent concrete structures' faults and cracks. Chung (1998) demonstrates this method by adding short carbon fibers to a concrete mix. The concrete, when attached with probes, exhibits a change in electrical resistance based on stress or deformation. The electrical resistance of the concrete increases when under stress, as the carbon fibers come closer together. Conversely, without being subjected to stress, the carbon fibers are separated, causing resistance to decrease.

Another example of sensing through inherent material properties are piezoelectric multi-material fibers with vibration sensitivity created by Wang et al. (2011). The fibers are a composite of Polyvinylidene fluoride (PVDF) in a poly(carbonate) cladding fabricated utilizing a thermal drawing process.

In this example, the oscillatory energy that mechanically disturbs the fiber causes the dispersed piezoelectric particles to generate an electrical signal. Since a change in the mechanical property generates electrical potential in the material, the fiber itself is actively sensing the change.

Given that piezoelectric materials are bi-directional transducers, they are utilized as inputs to sense vibration or output to generate vibration. In this case, the fibers can "hear and sing" as claimed by the authors.

The vibration generated by the fiber is a function of the fiber form factor, demonstrating the tight coupling between the host material (provider of property, form, and structure) and functional material (provider of transduction capability).

The multi-material piezoelectric fibers by Wang et al. (2011) are inspiring to this thesis as an example. More specifically, using vibration as stimuli that respond to changes in the mechanical property of the material. Section 4.2 presents an in-depth analysis on the use of vibration as a bottom-up approach to sensing.

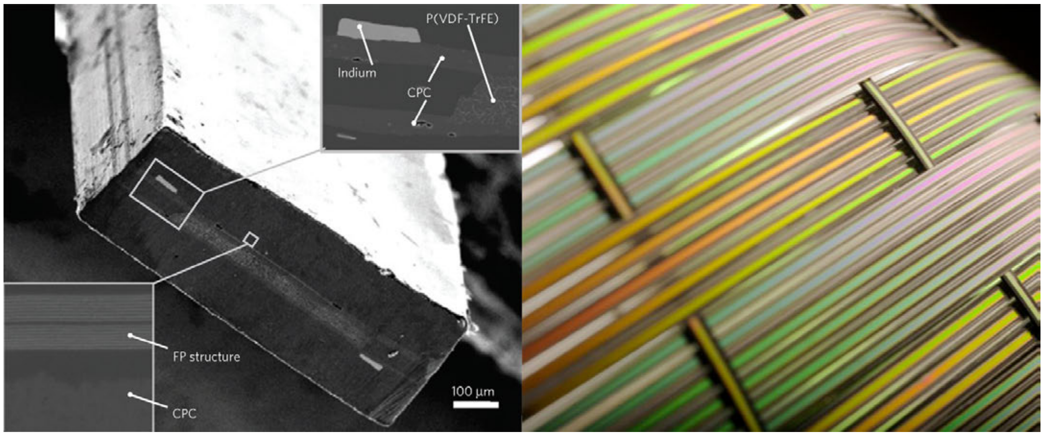


Figure 2.14: Image of piezoelectric fibers with acoustic sensitivity. *Left:* Cross section of piezoelectric fiber. *Right:* Image of mesh of fibers with acoustic sensitivity. *Source:* Wang et al. (2011)

2.3.4 Sensing Approach Trade Offs

If we exclude the requirements for power, hardware, software, and data processing to focus purely on the sensing technique, both top-down and bottom-up approaches offer advantages and disadvantages. The core advantage of a top-down approach is reliability and robustness. Since it utilizes industrially manufactured sensors, this method is robust with known documented characteristics available in a datasheet. Additionally, best practices for sensor structure and design have already been optimized and established in the industry.

Another advantage is that sensor packages are available in micro-scale footprints, allowing them to integrate into materials on a small scale. Lastly, advanced fabrication methods have been developed and optimized to enable the seamless integration of sensor nodes inside different materials.

On the other hand, a top-down approach can be potentially intrusive to a material; a sensor package or design will not always conform to the material properties and aesthetics. This integration method will result in a sensor-material hybrid rather than a material with sensing capability. Additionally, in many cases, to achieve a multimodal sensing, different types of sensor packages are required.

Meanwhile, this thesis argues that leveraging the potential of the material itself offers unique advantages. Since the bottom-up method uses properties that inherent to the material, it enables the exploration of multiple sensing modalities without necessarily including different sensors. An example of multimodality is the utilization of piezoelectric transducers to interface with a material's mechanical and thermal properties through the pyroelectric effect.

Another advantage is those specific material properties such as thermal conductivity, response to vibration are universal to every material, enabling the development of generalizable sensing techniques.

A disadvantage of a bottom-up approach is that not all properties of materials are suitable for sensing, Section 3.3 further discusses this topic. Additionally, to sense the property change, it requires the material to integrate means of transduction to interface with the material property. To preserve the characteristics and initial purpose of a material, it must transparently integrate with the transducer. Secondly, this integration must account for characteristics of a reliable sensor such as linearity, resolution, hysteresis, threshold, and repeatability (see NRC, 1995, p. 11), which may be a challenge depending on material and property.

Chapter 3

Material Inherent Sensing

“Every object made by man is the embodiment of what is at once thinkable and possible.”

— Ezio Manzini

3.1 Introduction

This chapter expands on a bottom-up approach to sensing by presenting a theoretical framework to develop materials with inherent sensing capability. It begins by introducing concepts from material science and sensing technology as base knowledge in devising a strategy to design and develop materials that can sense through their properties.

3.2 Material as a Platform

3.2.1 Materials and Properties

While a general definition of the word *material* describes the substance that composes objects and artifacts, materials are a multidisciplinary subject, and the meaning of the term varies radically depending on the approach.

The manipulation of materials dates back to the Stone Age with the use of stone, wood, and leather to satisfy human needs. Since then, the theoretical and practical knowledge of materials has evolved along with the means to process and develop new kinds of materials that extend the definition of the term per se.

Materials are known to have four interdependent dimensions: structure, properties, performance, and processing. These dimensions describe the means of creating and utilizing materials to satisfy the needs of a specific application (Callister, 1991).

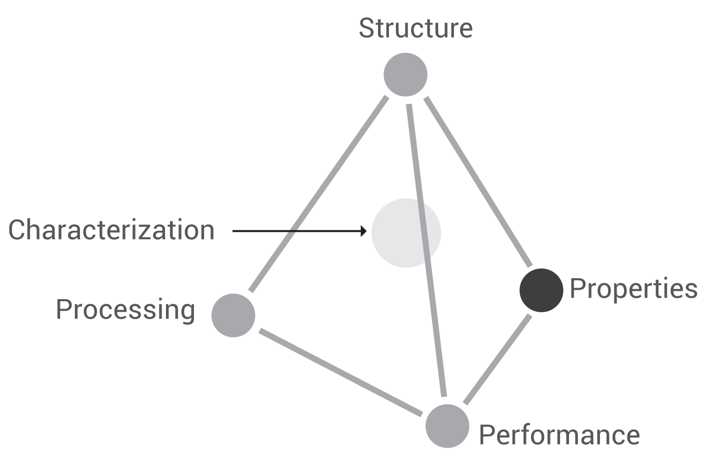


Figure 3.1: Diagram of the material paradigm highlighting Properties as the dimension of focus for this thesis. *Adapted from:* Zeiss (2020)

Structure

Material structure is the dimension that defines the structural component of materials across magnitudes. At a nanometer-scale, the structure of a material describes the arrangement of atoms and their nuclear interactions. An order of magnitude higher, the structure of material is the clustering of agglomerated atoms. At a macrometer-scale, the different groups of microscopic substructures form the macroscopic structure of a material.

Performance

Performance is a function of material properties and defines how a material performs under certain conditions. This dimension describes the suitability of a material to a particular application domain.

Processing

The processing dimension defines the structural elements of a material and describes the processes a material undergoes to gain a specific structure. Examples of processes for the development of materials are drawing, extrusion, casting, melt-spinning, rolling.

Properties

Lastly, the physicochemical properties of a material are the dimension of interest to this thesis. Physicochemical properties are the response of a specific property to external stimuli. These define how a material responds to input energy through its mechanical, thermal, electromagnetic, and chemical characteristics (Callister, 1991). Material properties and structure are the parameters used to categorize materials in groups.

For instance, metals are materials in which atoms arranged in an orderly fashion, mechanically stiff, durable, with high thermal and electrical conductivity, opaque and reflective optical properties. Ceramics are compounds of metallic and nonmetallic elements. Ceramics are relatively stiff and robust, known to be good insulators. Polymers are soft, low in strength, optically transparent. For instance, organic compounds compose most plastic and rubber materials. These exhibit low electrical conductivity and weak resistance to heat.

If we consider the response of a material property given external stimuli, for instance, the mechanical response of a polymer due to stress or the thermal response of metal due to an increase in temperature, properties can say a lot about the external stimuli through its natural response.

The basic concept of material properties outlined in this section is fundamental to the strategy for sensing through inherent material properties.

3.2.2 Functional Materials

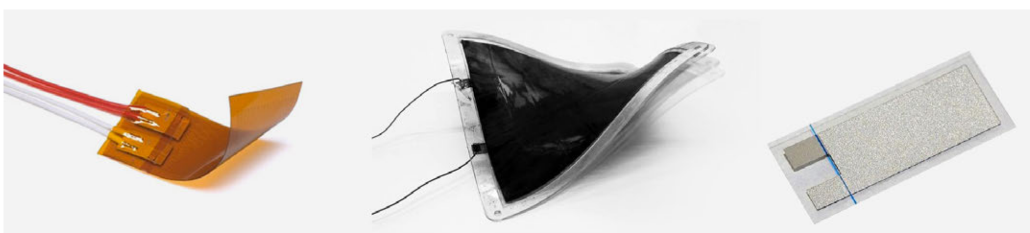


Figure 3.2: Image with examples of functional materials. *Left:* Thermocouple thin-film that converts change in temperature into an electrical signal. *Middle:* Electro Active Polymer: electrical to mechanical energy conversion. *Right:* Piezoelectric PVDF thin film bidirectional mechanical to electrical energy conversion.

Through innovations in material science and engineering, the discovery and synthesis of new materials have extended the capability of materials beyond the four dimensions of the material paradigm. Certain types of functional materials have, in addition to their intrinsic physicochemical properties, capabilities that blur the boundaries between physical and electrical properties.

Functional materials can exhibit the ability to convert input energy into electricity. Examples include piezoelectric, thermoelectric, pyroelectric materials that convert mechanical or thermal energy into an electrical signal (Figure 3.2). For instance, a thermoelectric material converts a change in temperature into an electrical potential. This capability makes these materials transducers between energy forms. The transduction of input energy into an electrical signal as output enables input energy to measured by an external device and further abstracted into sense-making measurands.

Noor et al. (2000) demonstrate the potential of functional materials for aerospace engineering. Authors propose using functional materials in the structure of airplanes to enable self-reporting of damage and fatigue caused by usage and environmental factors. Figure 3.3 demonstrates how functional materials can enable the coupling between different material energy fields. The basic knowledge of material properties and functional materials

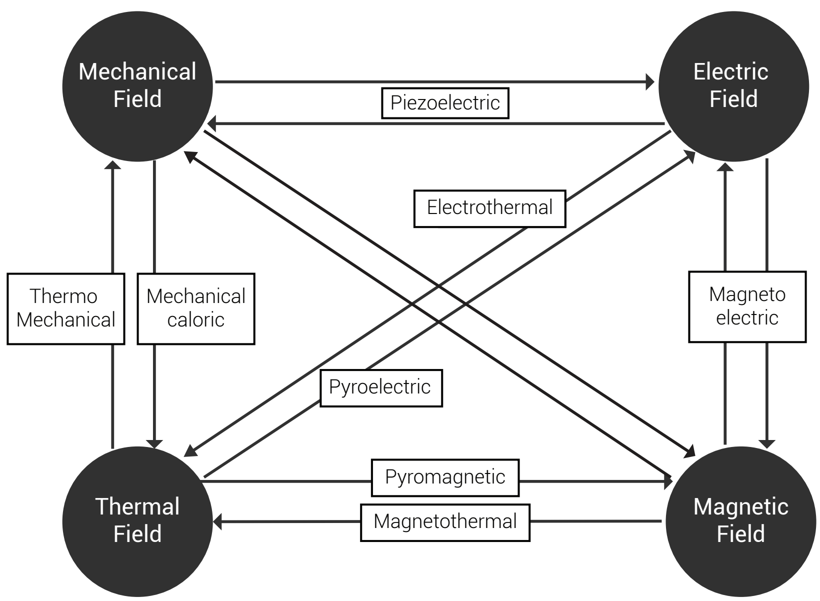


Figure 3.3: Couplings between different energy fields in smart materials.
Source: Noor et al. (2000)

is important to create a framework for the development of materials with inherent sensing capability as a bottom-up approach to sensing.

3.3 Framework for Material Inherent Sensing

The framework for material inherent sensing involves three fundamental elements that will be described in detail in the subsequent sections.

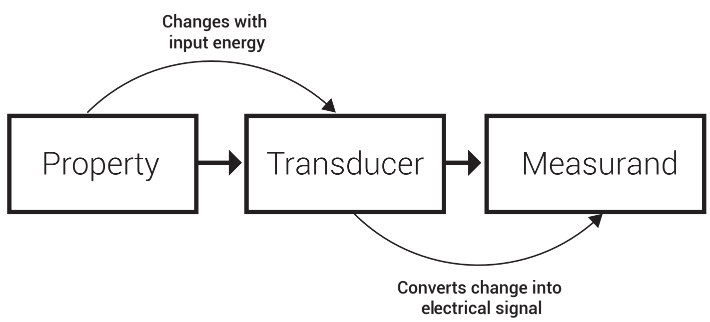


Figure 3.4: Diagram with the three required elements to enable material inherent sensing.

3.3.1 Property

Menges and Reichert (2012) suggest leveraging the "the embedded responsiveness" of a material as means to program actuation patterns in material structure. Authors propose to encode transformation in the structure of a material in response to humidity as means to generate shape change. The idea of leveraging an internal quality of material, in Menges' words "an embedded material capacity", is equally powerful when it comes to sensing interaction. However, instead of utilizing the material structure for output, this thesis proposes to leverage material property to sense input. Lang et al.

(2011) mentions a bottom-up approach is a viable method towards the development of "sensorial materials".

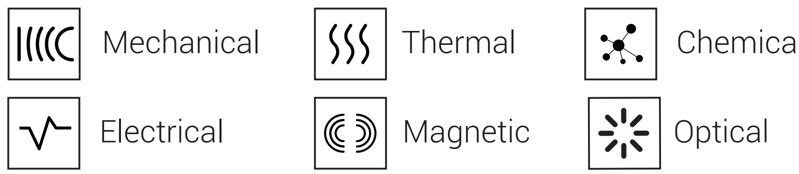


Figure 3.5: Diagram with six properties that are common to every material

The idea of sensing through intrinsic material properties can be expanded into a wider framework for the creation of materials in which properties become sensing enablers.

Table 3.5 shows six properties that are present in any category of materials. Each given property defines the characteristic of that material and the response of that property when subjected to external stimuli. For instance, applying stress to a metal bar will cause it to respond through its mechanical property by deforming. Equally, if the bar is heated, it will respond through its thermal property by a change in temperature.

Hence, if the change in the material property as a function of the external stimuli can be measured, the stimuli that generated change can be sensed. Similarly, if we observe the change in reflectivity (an optical property) of a ceramic material over the day, we observe that the material reflects less light as it gets dark. Hence, we can tell what time of the day it is.

If we unpack the six properties from Figure 3.5 into measurements for each property, it reveals a wide scope of sensing possibilities, as shown in Figure 3.6.

This is at the core of sensing through inherent material properties. The chal-

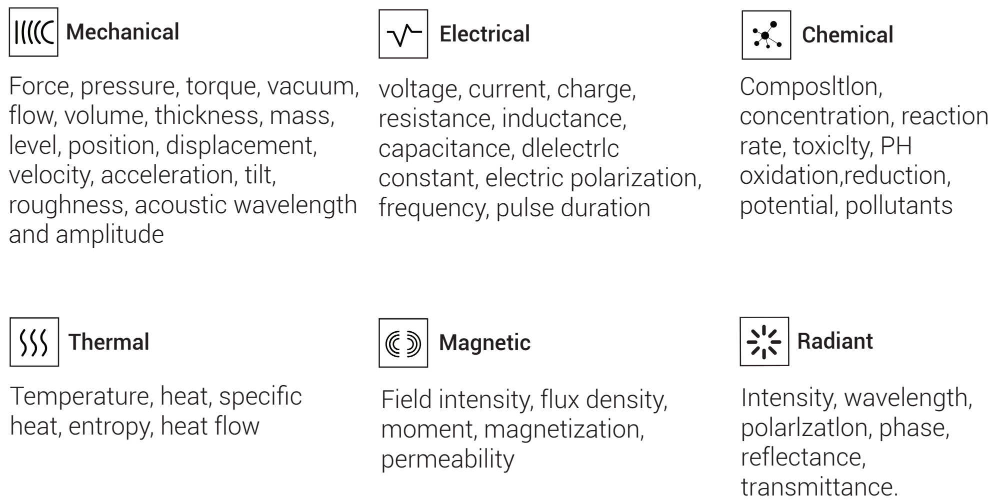


Figure 3.6: Diagram demonstration possible measurands for different material properties.

lenge is to find the means to measure the change in material response.

3.3.2 Transducer

Most materials cannot directly convert a change in property into a measurable signal. In order to measure changes in properties, it requires the instrumentation of the target material with a mechanism that can translate the change in property into a measurable signal.

The translation of change in property into a signal that can be measured externally is the role of a transducer. Middelhoek and Noorlag (1981) describe a general model for transduction between energy forms. In Figure 3.7, we can observe the translation of different energy forms (radiant, mechanical, thermal, magnetic, or chemical) between input and output through electrical modifiers.

Figure 3.7 shows that the measurement of a material property relies on the transduction of input energy into an electrical signal as the output of

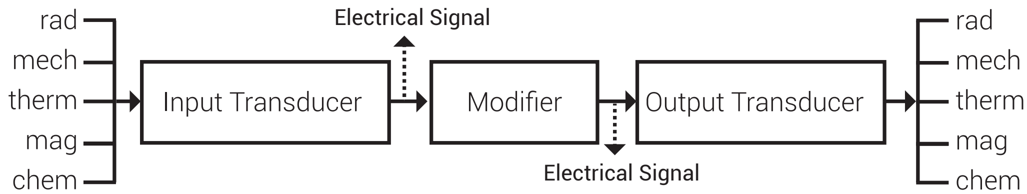


Figure 3.7: Diagram proposed by Middelhoek and Noorlag (1981) with the conversion of different energy domains.

the system. Moreover, as mentioned in Section 3.2.2, functional materials including piezoelectric, ferroelectrics, thermoelectrics, pyroelectrics are viable means of transduction. Hence, integrating a functional material into a host material is fundamental to sense changes in a given property.

The diagram in Figure 3.8 describes a general model for the relationship between the target material and the transducer. A functional material captures the change in the target material caused by external stimuli and outputs an electrical signal. Once the internal changes in material properties

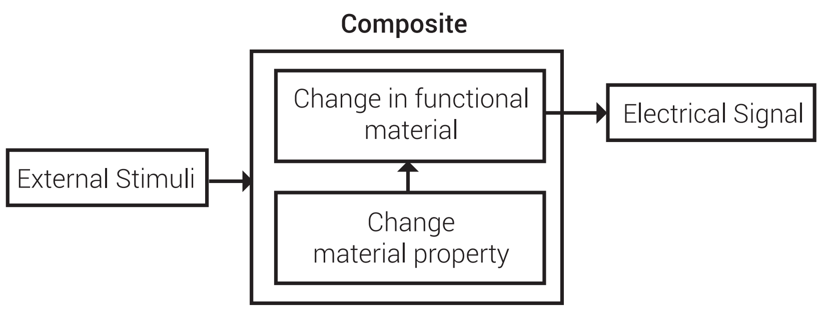


Figure 3.8: Diagram that describes the relationship between the target material and the transducer.

convert into electrical signals property changes become useful values for measurement and decision making.

3.3.3 Measurands

The electrical property of a material is the most commonly used signal to sense interaction as it does not need means of transduction for measurement. For example, changes in resistance or capacitance of a conductive material given external stimuli have been the basis for a number sensing modalities Gong et al. (2011).

If the scope for sensing through material properties expands from electrical properties to other inherent material properties, novel sensing modalities may become possible.

For example, we can measure the force, position, and displacement, acoustic wavelength, and amplitude of an external energy by leveraging the mechanical property of a material integrated with a piezoelectric transducer.

Similarly, the optical response of material through the photovoltaic effect can reveal the intensity, wavelength, reflectance, and transmittance of a light source.

Lastly, the thermal properties of a material such as a change in temperature, heat, entropy, and thermal flow can provide insight into the source of heat energy that caused the change in the material. Figure 3.9 demonstrates the numerous possibilities for sensing through material properties.

The integration of a transducer in a material can occur in different configurations and length scales which will be covered in the next section.

3.4 Functional Composites

Callister (1991) describes the several methods for combining two or more materials into a composite. Similarly, Bosse et al. (2016) demonstrates how to integrate materials with sensors. The method for compositing is depen-

Material Property	Transducer	Effect	Measurand
Electrical	No need for transducer	Conductivity, Resistance, Capacitance	Voltage, current, charge, resistance, inductance, capacitance, dielectric constant, electric polarization, frequency, pulse duration
Mechanical	Piezoelectrics	Piezoelectricity Piezoresistance,	Force, position, displacement, velocity, acceleration, tilt, roughness, acoustic wavelength and amplitude
Optical	Photo Detector Solar Cell	Photovoltaic, Photoconductivity	Intensity, wavelength, polarization, phase, reflectance, transmittance
Thermal	Thermocouple, Thermoresistor, Pyroelectrics	Seebeck Effect Thermal Resistance Pyroelectric Thermo-dielectric	Temperature, heat, specific heat, entropy, heat flow
Magentic	Magnetoelectric	Hall Effect Magnetoresistance	Field intensity, flux density, moment, magnetization
Chemical	Galvanic Cell	Ionization, Potentiometry Volta effect Gas sensitive field effect	Permeability, composition, concentration, reaction rate, toxicity, oxidation-reduction potential, pH, pollutants

Figure 3.9: Table with common material property responses, means of transduction, and sensing measurands. *Adapted from:* NRC (1995)

dent on the material property used as a sensing enabler, length scale of integration, form factor of the functional material, and application of the final composite.

Methods of composting functional materials to harness material properties can include: the dispersion of particles, short or long fibers from a functional material in the matrix of a target material. Other techniques involve stacking laminar layers of the functional and target material.

The creation of a material with inherent sensing properties can use numerous methods of integration between functional and target materials already reported in literature (see Callister, 1991, p. 634). However, it is essential to establish a set of design principles for the successful creation of a composite with inherent sensing capability:

- The transducer has to output an electrical signal based on a property response of a target material.
- The target material's initial purpose, aesthetics, and properties must not be changed by integrating with the functional material.
- The functional material must transparently be integrated into a target material resulting in a homogeneous composite.
- The compositing method has to maximize the coupling between the property response from target material as a sensing enabler.

The objective of a composite made from a target and functional material is to leverage the material property response for sensing. Hence, the composition of the two materials envisages creating a mutually beneficial relationship between the two. At the same time, the functional material harnesses the property response of the target material. The target material provides structure, form, and an inherent property as a sensing enabler.

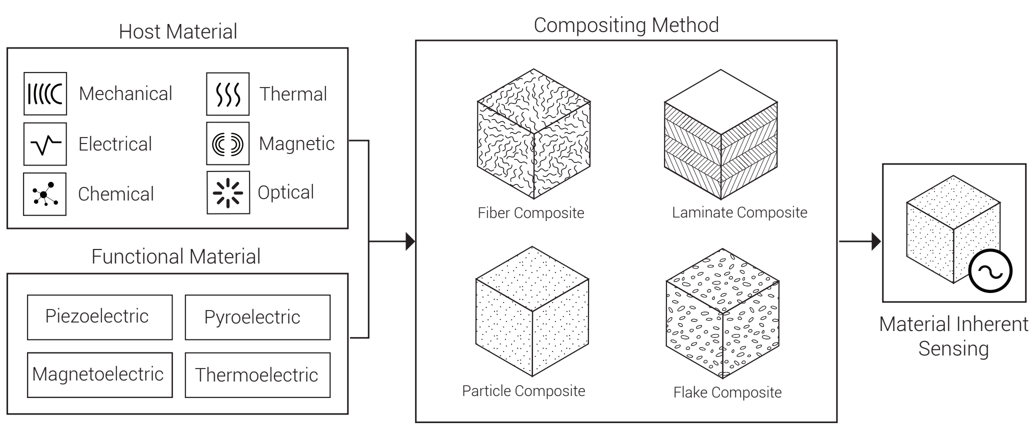


Figure 3.10: Diagram that summarizes a strategy for material inherent sensing.

Figure 3.10 illustrates the framework for developing materials with inherent sensing capability. To summarize the steps involved in the framework: First, select one or more properties of a material as sensing enabler, the sensing objective determines the selection of this property. Secondly, a material for transduction of that property has to be defined based on the property selected (as shown in Figure 3.9) and, lastly, a method of integration between the functional material and target material defines the fabrication method and configuration of the functional composite.

3.5 Challenges & Considerations

The performance of a property response of a material as a sensor takes into consideration several factors:

First, the accuracy of the output signal will depend on the property response selected and the ability of the functional material to transduce the change in the chosen property response.

Second, the response time to external stimuli will vary based on property and material. For instance, metals exhibit a higher thermal conductance then polymers. Thus, they may exhibit a faster response in property change when subjected to heat than a polymer.

Third, most properties will exhibit a non-linear response to stimuli. Hence the response of a property has to be characterized and modeled to be useful for measurement.

Fourth, regardless of the property selected, a material will exhibit an operating range in response to external energy before breakdown. In that case, the ability to sense the external stimuli will depend on the breakdown limit of that material given an energy source.

Although this approach may have limitations, the development of materials with inherent sensing capability shows promise to take steps closer to the development of technology that blends with the environment.

3.6 Mechanical Vibration as a Sensing Enabler

This thesis proposes a further exploration into using mechanical properties of a material as a sensing enabler to demonstrate the potential of inherent material sensing, as a bottom-up approach. More specifically, analyzing the mechanical response to vibrational waves as the means to sense interactions with that material.

While mechanical properties are often associated with the behavior of a material at a macro scale, materials respond mechanically to forces at much smaller scales such as vibrations generated by an oscillating force at scales ranging between 10^{-11} and 10^{-3} meters (Cremer et al., 2005).

As previously mentioned, the benefit of using vibration as an inherent material property is that any material vibrates when subjected to an oscillating force. Vibrations propagate through the extent of material even when generated by weak forces. It is a phenomenon that can be accurately measured and exhibits a fast response time. Lastly, vibrational waves on materials, if examined in detail, can reveal a rich set of information about the source of vibration.

Chapter 4

Vibroacoustic Materials

"If I'm sitting next to a swimming pool, and somebody dives in [...] I think of the waves and things that have formed in the water. And, uh, when there's lots of people have dived in the pool there's a very great choppiness of all these waves all over the water and to think that it's possible, maybe, that in those waves there's a clue as to what's happening in the pool. That some sort of insect or something with sufficient cleverness could sit in the corner of the pool and just be disturbed by the waves, and by the nature of the irregularities and bumping of the waves have figured out who jumped in where and when and what's happening all over the pool."

— Richard Fenyman

4.1 Introduction

This chapter focuses on leveraging vibration, a material mechanical property, as an example of a bottoms-up approach to sensing. It first introduces concepts from vibroacoustics and piezoelectrics as base knowledge for creating material with vibroacoustic sensing capability.

4.2 Material Vibration as Sensing Enabler

4.2.1 The Anatomy of Vibrational Wave

A wide range of disciplines including physics, acoustics, audio engineering, psychoacoustics, aeroacoustics, bioacoustics, underwater acoustics study behavior of vibrational waves in solids and fluids.

The phenomena of acoustic vibration involve the propagation of waves in fluids and solids (Smith et al., 1965). A wave travels through the expansion and compression of molecules of a medium. In the case of air, the result of the compression and expansion of air molecules is what we perceive as sound (Figure 4.1).

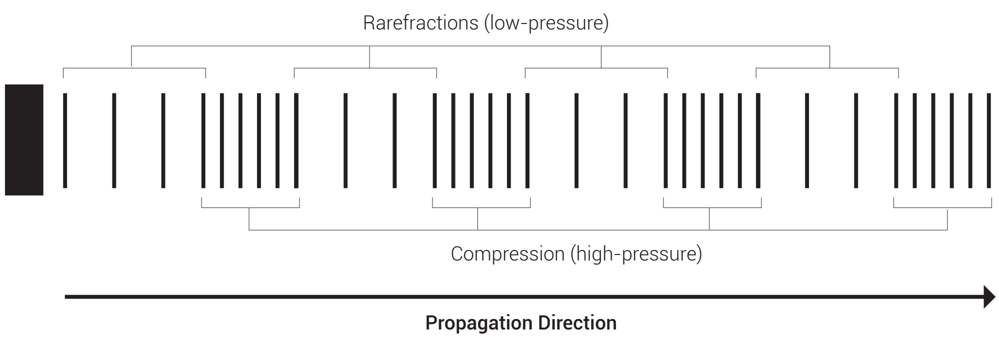


Figure 4.1: Diagram showing the rarefraction and compression caused by the propagation of an acoustic wave in air. *Adapted from:* Berg et al. (1982)

Sound and vibration are intrinsically related. A significant part of sounds originates from vibrations in solid materials. For instance, a stone hitting the floor, the wind blowing through the window, strumming the strings of a guitar. These sounds are created by vibroacoustic waves that originate in solid materials Cremer et al. (2005).

Since an acoustic wave is kinetic energy passed from one molecule to another, its speed varies depending on the medium of transport. The further apart molecules are in a medium, the slower the wave will travel. Given this characteristic, waves propagate faster in solids than liquids or gas.

Acoustic waves can generate mechanical vibration in bodies without causing damage, making it a non-invasive and non-radiative technique for sensing. The frequency of propagation of a wave can range from values below 20Hz to values above 200Mhz, with each frequency range corresponding to a specific area of application.

Frequencies below 20Hz (infrasound) are useful for the prediction of earthquakes. The audio industry uses the range between 20Hz and 20kHz (the human audible range) in applications that interact with human speaking and hearing capabilities. Biomedical applications use frequencies above 20kHz, these include ultrasound imaging, manipulation of cells and neural excitation. Frequencies above 200MHz are utilized in acoustic microscopy to image internal features of material in a non-destructive manner (Ma, 2019).

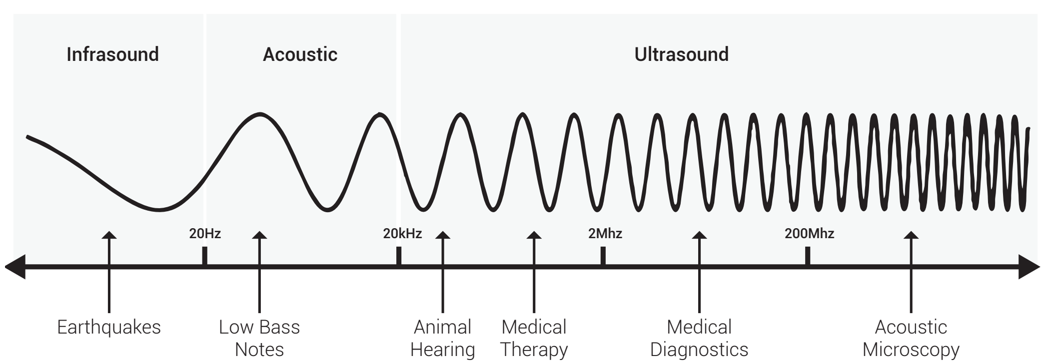


Figure 4.2: Diagram of the frequency spectrum and applications. *Source:* Ma (2019).

Compared to electronic and mechanical sensors, acoustic vibration offers multiple advantages. First, it is non-destructive to the target material. It can sense through direct or indirect contact with a target. Second, it supports a wide range of applications based on the frequency range of interest. Third, the relatively slower speed of propagation, compared to radio-frequency (RF), enables accurate measurement of a given phenomenon (Cai et al., 2019). Fourth, it is uniquely useful for underwater communications and sensing. On top of those advantages, vibration transducers can be produced at low cost and deployed at scale.

This thesis focuses on wave propagation in solid materials. For further discussion on the theory of sound and acoustic waves, refer to (Strutt, 2011).

4.2.2 The Acoustic Process in Solids

Cremer et al. (2005) proposes that the process of structural vibration comprises of four sequential stages (Figure 4.3).

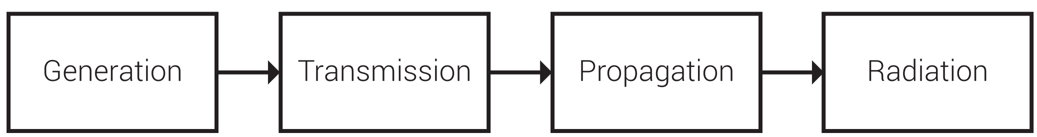


Figure 4.3: Diagram with the four stages of structural acoustic process proposed by Cremer et al. (2005).

The first stage is the active mechanism that generates oscillatory energy. The second stage refers to a mode of transmission that carries the oscillatory energy to a passive system. Consequently, waves propagate through the passive system subjected to the energy source. Lastly, the vibratory motion propagated through the passive system radiates to another medium.

Focusing on the propagation stage of the acoustic process, subjecting a material to an oscillating force causes a complex set of vibrational energies to irradiate out from the point of contact between the object generating the oscillatory energy and the passive system.

This wave field is composed of several wave modes that deform the material. These waves oscillate at different frequencies and amplitudes. To demonstrate the richness of information in vibration propagation this thesis proposes the following scenario.

4.2.3 Inferring Interaction from Vibration

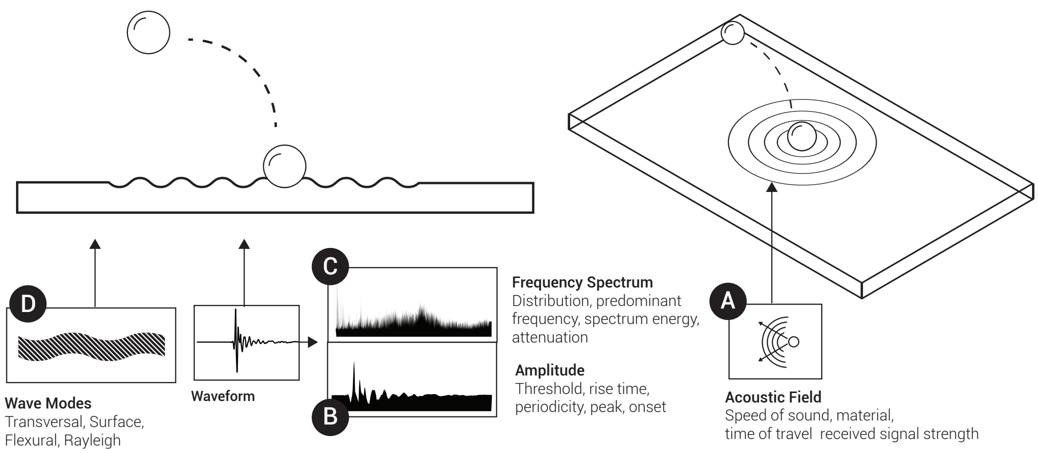


Figure 4.4: Diagram illustrating different information that can be extracted from propagation of waves on the table material.

Inside a room, a person throws a marble ball on top of a wooden surface. First, the hand that throws the ball generates vibrational energy transferred to the marble ball, once the marble ball collides with the surface, the ball's energy transfers to the wood material. A series of vibrational waves propagate outwards from the point of contact between the marble and the wooden surface. These vibrations are attenuated by the wood and then irradiate from the solid surface into the air, generating the sound of the impact.

The inter material interactions in this scenario can reveal a wealth of information about the event from a vibroacoustic point of view:

1. The geometry of the wave field that irradiates out from the point of contact between the marble ball and surface can inform the location of an impact between the two bodies. (Figure 4.4.A)
2. The amplitude acquired from waveform generated by the collision can reveal information about the energy of impact, speed, and size of the marble ball (Figure 4.4.B)
3. The frequency components can reveal information about the ball and surface material properties, for example, whether the ball material is soft, hard, elastic, and so forth. In addition to predicting the speed of the ball and gesture that caused the collision. (Figure 4.4.C)
4. Wave modes that propagate through the surface are attenuated by its other material properties. This reveal details about dimensions and material composition of the surface (Figure 4.4.D)

Figure 4.5 shows the four dimensions of information that emerge from the collision event using the mechanical properties of the surface as a sensing enabler.

4.2.4 Vibration as Information

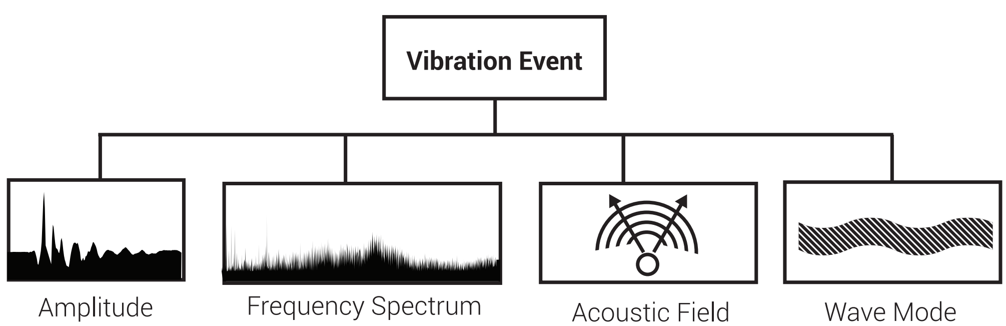


Figure 4.5: Diagram with different dimensions of information that can be extracted from the collision event.

Amplitude

The amplitude profile of the waveform over time (rise, sustain, and release moments), can identify the nature of the vibrational event. For instance, a collision between two materials will likely exhibit a high amplitude compressed in a short period of time. Additionally, peaks and onsets in the waveform can be detected to determine the periodicity of the vibrational event.

The energy of the vibration source can be calculated by mathematically integrating time and amplitude. Profiling the waveform's rise and decay moments can reveal the duration of the vibrational event.

For example, on Scratch Input, Harrison and Hudson (2008) utilize the changes of amplitude and frequency characteristics to discriminate between different scratch gestures on a surface. In TouchLight, Wilson (2004) utilizes the amplitude of different gestures to distinguish a tap from a knock. The latter is recognized by detecting a peak above a defined threshold.

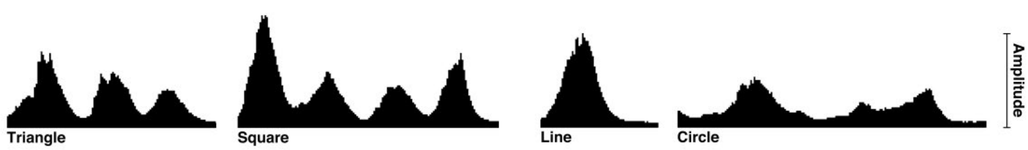


Figure 4.6: Diagram extracted from Scratch Input paper. Amplitude profiles can be noticed for each shaped scratched on a surface. *Source:* Harrison and Hudson (2008)

Frequency

The spectral components of a waveform in the frequency domain, including frequency distribution, fundamental frequency, spectrum energy, can be utilized to classify the vibration source.

Machine learning models commonly use frequency components to perform prediction and classification based on the spectral characteristics of the

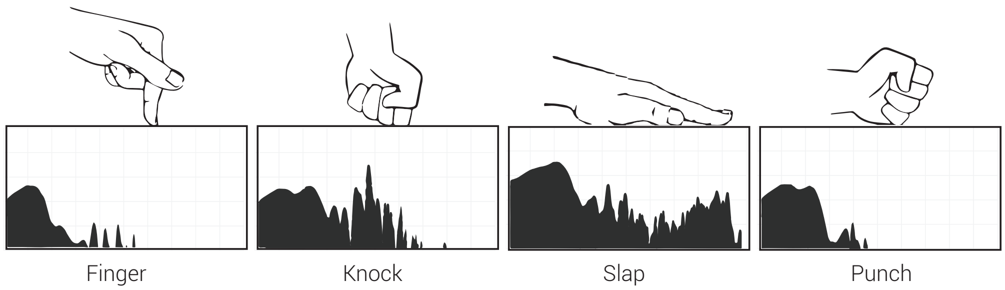


Figure 4.7: Diagram adapted from Touch Light showing different frequency distribution for each gesture when touching a surface. *Adapted from:* Lopes et al. (2011)

event.

As an example, TapSense (Harrison et al., 2011) augments touch displays using acoustic sensing to classify finger, nail, or knuckle taps by analyzing the frequency distribution of each gesture on a spectrogram. Lopes et al. (2011), propose techniques to augment interaction by classifying different types of touch with a single acoustic sensor by analyzing the amplitude envelope and frequency distribution of each class of gestures.

Laput, Brockmeyer, Hudson and Harrison (2015) design a series of 3D printed mobile phone attachments that use device microphone and speaker systems to generate unique spectral signatures used to discriminate between different interactions with the phone attachments.

The attenuation of specific frequencies on a medium can help in discriminating between interactions. Ono et al. (2013) demonstrate this technique in Touch & Activate. Authors utilize a vibration source as a sweep signal. A receiver with a Fast Fourier Transform (FFT) analyzer profiles the frequency response. Utilizing a support-vector-machine (SVM) model as a classifier, the system can discriminate between different touch gestures and interactions in several objects (Figure 4.8).

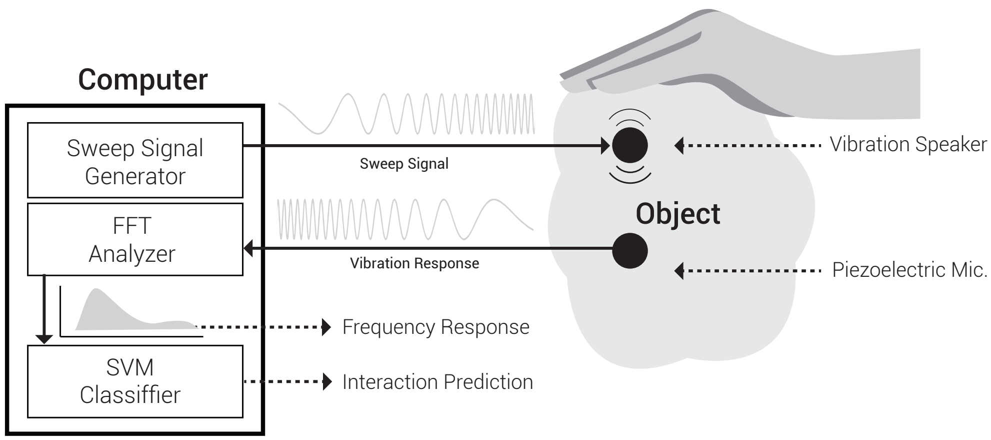


Figure 4.8: Diagram adapted from Touch & Activate paper. Overview of system utilized by authors to classify interactions. *Source:* Ono et al. (2013)

Wave Field

An acoustic field is composed of multiple wavefronts that originate from the point of contact of the initial displacement pulse and expand outward as a circle increasing in radius. The amplitude of the pulse decreases as the circular wavefront expands as a means to conserve energy. Different techniques use the travel time of the wavefronts at different frequencies to localize the origin of a vibrational pulse.

Conventional techniques include Time of Arrival (TOA) to estimate the source event position by knowing the speed of sound in the medium, the exact time that the pulse occurs, and the exact time the pulse arrives at a reference point.

Time Difference of Arrival (TDOA) localizes the origin of a pulse without knowing the exact time of the initial pulse. It calculates the source's position based on the difference in the time that pulse arrives at two or more reference points. Figure 4.9 illustrates these approaches. Section 5.3.1 describes specific implementation details for TOA and TDOA approaches.

Ishii et al. (1999) utilizes the TDOA technique to locate the impact of a ball

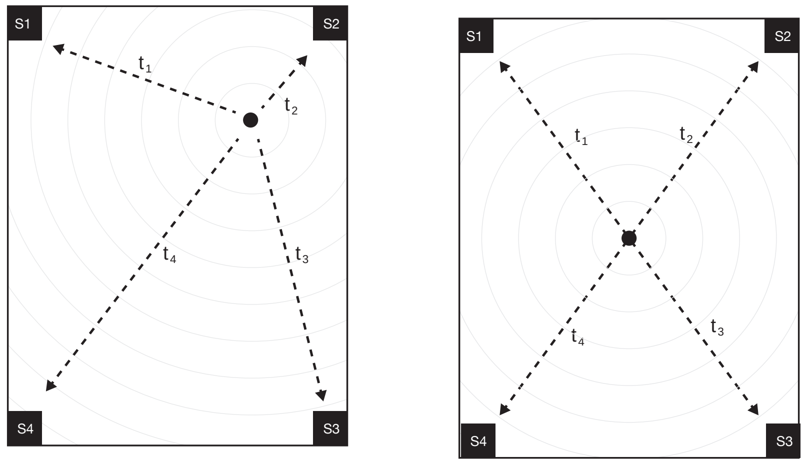


Figure 4.9: Diagram illustrating basic concept of ToA and TDoA. *Left:* Pulse at the center of a plane in which t_1,t_2,t_3,t_4 arrive at reference points s_1,s_2,s_3,s_4 exact at the same time. *Right:* If origin of the pulse is at the top right corner travel time t_1,t_2 is smaller than t_3,t_4 to arrive at s_2. Whilst this diagram uses 4 reference points for pulse arrival. ToA and TDoA require a minimum of 2 reference points.

on a ping pong table. The technique developed by the authors uses eight contact microphones, four for each side, on the corners of the table. On impact, the ping pong ball triggers a peak detector that computes the difference in the time domain to estimate the impact position. Figure 4.10 illustrates the implementation of PingPongPlus.

Paradiso et al. (2002) demonstrate a localization technique on a 2 x 2 meters glass surface with four piezoelectric contact microphones applied to the corners of the glass. To localize touch, authors utilize TDOA by computing the cross-correlation across signals from pairs of sensors. Through this method, they estimate the time difference of arrival from the correlation peak. With this technique, the authors report a resolution of 2cm for touch gestures.

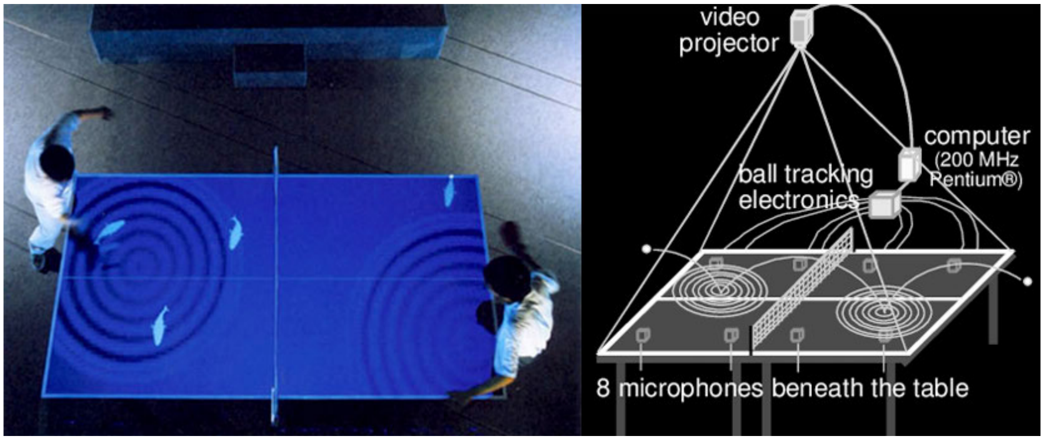


Figure 4.10: Images extracted from PingPongPlus paper. *Left:* Image of table projection responsive for ping pong ball impact. *Right:* Diagram showing the wave field and position of microphones. *Source:* Ishii et al. (1999)

Wave Modes

When a vibration source is in contact with a medium, multiple types of vibrational waves are generated. The propagation of waves can reveal properties and characteristics of the medium in which the waves are propagating since certain wave types are specific to a medium.For example, solids materials exhibit four main wave modes:

- Longitudinal waves: parallel to the direction of the wavefield
- Transversal (or shear waves): perpendicular to the direction of energy. These waves are weaker in relation to longitudinal waves.
- Surface Waves: emerge in bulkier material from the combination of longitudinal and transverse motion. These, when combined, generate an elliptical orbit that also called Rayleigh waves.
- Lamb Waves: appear in thinner materials and propagate parallel to the surface through the material thickness. They can be symmetrical or asymmetrical. The asymmetrical Lamb wave is also known as a flexural wave.

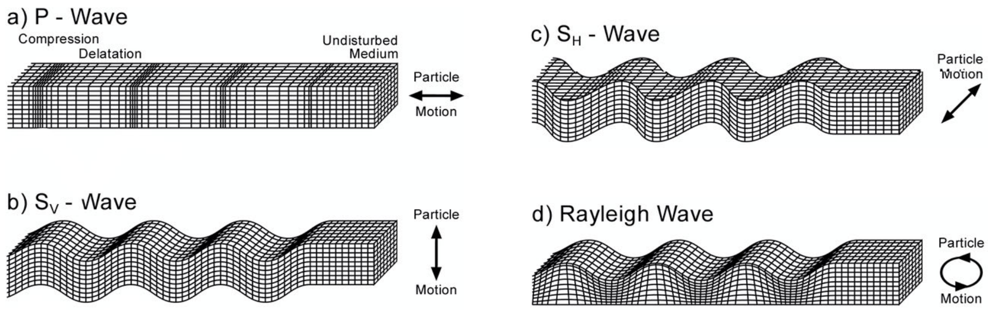


Figure 4.11: Diagram with different wave modes generated in solid body by an oscillating source. *Source:* Bruce (1988)

Nikolovski (2013) implements a system for selective detection of Lamb wave modes to perform localization of touch on a surface by flick or fingernail with TDOA technique.

This approach was first demonstrated by Nikolovski and Fournier (1994) and evolved over ten years of research to develop an acoustic surface with multimodal input and output. It supports touch interactions and can operate as a microphone and speaker that captures and transmits sound waves.

4.3 Interfacing with Material Vibration

There are several ways to interface with material vibrations; the most commonly used device to capture vibrations is a microphone. Traditionally a microphone is a device that transduces variations in air pressure into an electrical signal. It encompasses a broad frequency range and often excludes vibrations at a very low-frequency (Fraden, 2016).

The main characteristics of microphones are their sensitivity, directionality, dynamic range, and working principle. Given the mechanical nature of acoustic waves, microphones have the same working principle as pressure sensors: a moving diaphragm displaces bases on pressure waves; the displacement translates into an electrical signal.

Common types of microphones include resistive microphones in which a semiconductive diaphragm changes resistivity based on pressure. Condenser microphones use two conductive plates (one is a moving diaphragm) that converts the change in distance between the two into an electrical signal.

Fiber optic microphones use an interferometer and reflective plate diaphragm in which plate deflection translates to an electrical signal. Electret microphones consist of an electrically polarized crystalline dielectric material. An electrostatic microphone is a transducer with a metallic electret and backplate separated by an air gap, and lastly, piezoelectric microphones make use of piezoelectric properties of materials to generate electricity when subjected to mechanical stress.

While not commonly used audio engineering applications, piezoelectric microphones are useful to sense vibration given their sensitivity, frequency range, and availability in formats that can integrate with materials across scale.

4.3.1 Introduction to Piezoelectrics

Figure 4.12: Image of piezoelectric crystal. *Source:* GreenAge.

Piezoelectric (Greek word for “pressure” electricity) is a phenomenon that was discovered by the Curie brothers in the 1880’s by observing that quartz crystals changed dimensions when subjected to an electric field. The phenomenon was then used by french physicist Paul Langevin in 1920 to create the first sonar by using quartz as a receiver and transmitter pair.

The piezoelectric effect was then observed in different materials such as ceramics when subjected to polarizing voltage. In the 1960s similar effect was observed in whalebone and tendon, which drove the search for the effect in organic materials. In 1969 Dr. Heiji Kawai found a piezoelectric effect in polarized fluoropolymer (PVDF), expanding the availability of piezoelectric materials from ceramics to polymers.

4.3.2 Piezoelectric Effect in Materials

A model proposed by Prof. Alexander Meissner in 1927 demonstrated the effect at the molecular level of the piezoelectric material.

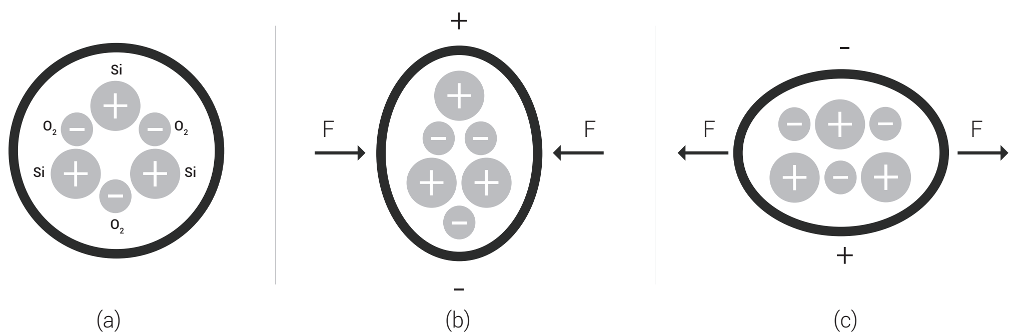


Figure 4.13: Diagram of piezoelectric effect at a molecular level proposed by Professor Alexander Meissner in 1927. *Source:* Fraden (2016)

Based on the Meissner model, a piezoelectric Quartz Crystal has a helix structure with three silicon atoms and three pairs of oxygen atoms. Each silicon carries four positive (+) charges; each oxygen pair carries four negative (-) charges (two per atom). In this configuration, the cell is electrically neutral, with no force applied (Figure 4.13.a).

Under the force F, the horizontal axis compresses, the hexagonal lattice deforms, its deformation rearranges the atoms. Positive charge accumulates at the atom side on the Y-axis, while negative charge accumulates at the oxygen pair side on the X-axis. (Figure 4.13.b)

Conversely, if a force is applied in the opposite direction the same charges accumulate, but in opposite polarity (Figure 4.13.c)

4.3.3 Piezoelectric Materials as a Vibration Interface

The piezoelectric effect can exist in a wide diversity of crystals and ceramics. Advances in material science and engineering have enabled the synthesis of polymeric piezoelectric material. Materials such as polyvinylidene fluoride (PVDF) and its co-polymer (PVDF-TrFe) exhibit piezoelectric characteristics and is available in diverse formats, including thin film, pellets, powder, ink. Piezoelectric transducers are available as packaged sensors that include electrodes and interfacing connectors.

Bidirectional Transduction

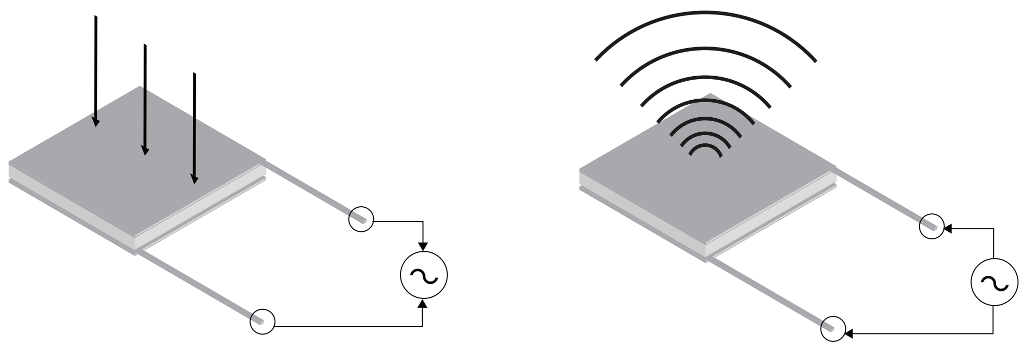


Figure 4.14: Illustration of piezoelectric material converting force into an electrical signal and vice verse. *Left:* Electrical response generated by force applied. *Right:* Material vibration generated by electrical excitation.

Materials that exhibit piezoelectric response are inherently bidirectional transducers that convert mechanical force into an electrical signal and vice versa. When subjected to vibration, the piezoelectric material expresses an alternating electrical signal. Conversely, if subjected to an alternating electrical signal, the material will vibrate at the signal frequency. The mechanoelectrical capability of piezoelectrics makes it a unique material that can be used as a sensor and an actuator, as shown in Figure 4.14.

Multiaxial Response

Piezoelectrics have axis dependant electrical responses. This dependence is related to the orientation of the dipoles in the molecular structure of the material. Given this characterististic, the electrical response varies depending on which axis is displaced by an external force. For instance, a piezoelectric material polarized in the Z-axis will exhibit a higher electrical response if a force is applied normally to the surface of the material. Conversely, a piezoelectric material polarized in the X-axis will exhibit a higher electrical response when laterally compressed or expanded. This relationship is illustrated in Figure 4.15. The multiaxial response of piezoelectric material can make it sensitive to changes in a given direction of force or distortion of the material.

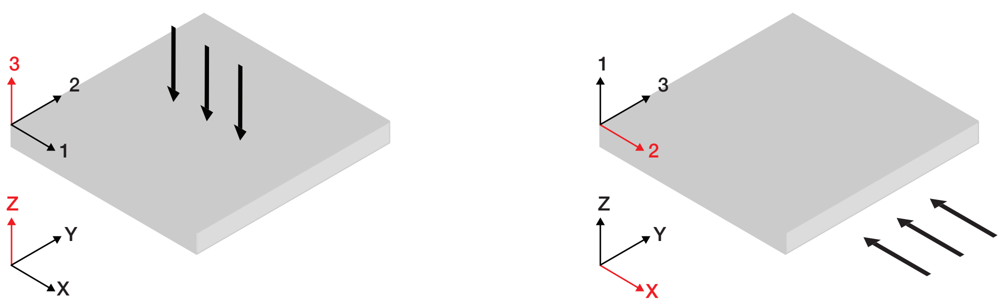


Figure 4.15: Diagram of multiaxial response of a piezoelectric material. *(a)* Piezoelectric material that exhibits electrical response in the 3rd axis (Z axis). *(b)* Piezoelectric material that exhibits electrical response on the 2nd axis (X axis) piezoelectric axis response.

Wide Frequency Range

When it comes to the frequency response, a piezoelectric material will oscillate at the same frequency as the source of mechanical displacement. Piezoelectrics polymers such as the PVDF are known for having a frequency response in the range between 0.001Hz to 10^9Hz (see PiezoTechnicalManual, 2020, p. 2). Hence, piezoelectric materials are highly sensitive to a wide range of vibrations. Making it suitable for applications in the infrasound, acoustic, and ultrasound frequency ranges.

Natural Voltage Output

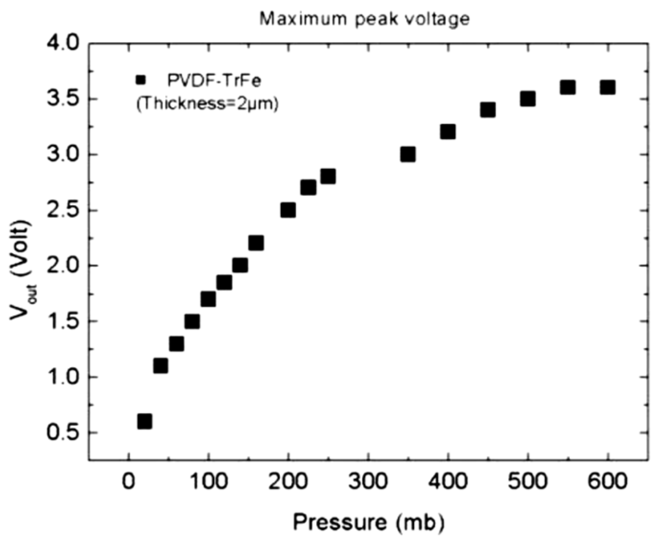


Figure 4.16: Plot of electrical response for a Arkema Piezotech FC 25 ink P printed sensor (voltage obtained by applying gas flow) *Source:* Arkema (2020)

Another quality of piezoelectric material is the ability to express a natural output voltage as a function of mechanical stress, as shown in Figure 4.16. Unlike capacitive or resistive sensing techniques, piezoelectrics do not require a voltage excitation. Piezoelectrics are also commonly used as energy harvesters.

Material Diversity

Several materials that exhibit piezoelectric characteristics can be naturally sourced and synthesized. Piezoelectric materials exist in the family of crystals such as Lead zirconate titanate (PZT), Barium titanate ($BaTiO_3$). Additionally, piezoelectric polymers such as polyvinylidene fluoride (PVDF) and co-polymer (PVDF-TrFe) are available in the form of fibers, yarns, powder, and ink, as shown in Figure 4.17. This versatility attributes transparency to the piezoelectric material to integrate into other materials as an energy transducer seamlessly.

Figure 4.17: Image with types of piezoelectric materials *a.* PVDF poled piezoelectric film with silver ink electrodes*b.* .P(VDF-TrFE-CFE) Terpolymer *c.* .PVDF Homopolymer Pellets *d.* .P(VDF-TrFE) Copolymer Resin *Source:* (PolyKTechnologies, n.d.)

In summary, the combination piezoelectric characteristics: versatile material form, natural voltage output, frequency range, and bi-directionality makes it into the ideal element to interface with material vibrations.

4.3.4 Challenges Working Piezoelectric Materials

Polling

While piezoelectric materials can express electrical potential when subjected to mechanical stress, in many cases, the material requires treatment to increase electrical response. This treatment involves a process known as poling. Poling orients the molecular structure of piezoelectric material to a phase (known as the β phase) in which the material exhibits higher electrical response due the configuration of molecules in the material matrix. (Figure 4.18).

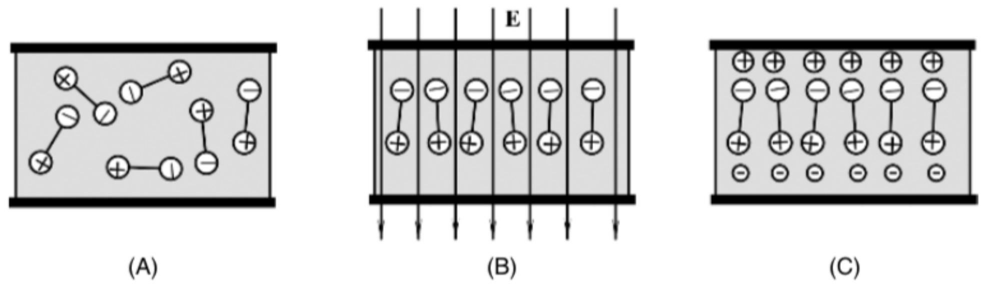


Figure 4.18: Diagram of dipoles in molecular matrix of a piezoelectric material. *A.* Dipoles randomly oriented in material molecular matrix. *B.* Dipoles forced in orientation by electrical field *C.* Dipoles permanently re-oriented in material molecular matrix. *Source:* Fraden (2016)

The polling process involves subjecting a material to a high electric field (in the magnitude of kilovolts) through a sustained amount of time while heating the material to a given temperature. This process reconfigures the molecular structure of the material, and by consequence, the material will exhibit a higher piezoelectric effect.

The polling process involves tuning several correlated parameters (poling voltage, wave type, material thickness, temperature, polling system design, electric field periodicity) that are nontrivial and require a large amount of trial and experimentation. The polling process is a challenge for manual and DIY fabrication since it requires special equipment and development of a material-specific recipes.

Structural Requirement

The second challenge when working with piezoelectrics is to acquire the electrical charge generated by the material efficiently. Hence, the material has to be “sandwiched” between a top and bottom electrodes, as shown in Figure 4.19.

In terms of fabrication, it involves the deposition of a base conductive layer at the bottom, the piezoelectric material in the middle, and a second, con-

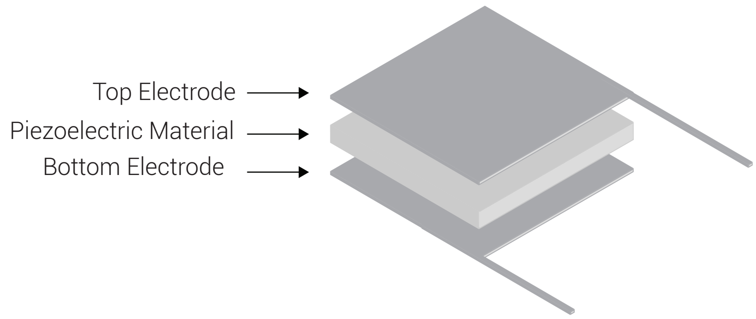


Figure 4.19: Diagram with isometric view of layer structure from piezo-electric thin film.

ductive layer, at the top. Lastly, the fabrication method has to account for attaching leads or contacts to the material electrodes. The fabrication of piezoelectric sensors requires specific equipment to deposit electrodes on the piezoelectric material surface evenly.

Electrical Properties

The structure of a piezoelectric transducer is the same structure of a capacitor. Top and bottom electrodes with an inner dielectric material. Capacitive structure causes the piezoelectric transducer to collect charges from other sources rather than the piezoelectric material itself, including environmental noise and capacitance from other elements that interact with the transducer.

Shielding and grounding the transducer are required to mitigate this issue. Additionally, piezoelectrics are known to have a high impedance (Z), which requires special consideration when interfacing with a readout circuit. Section 5.4.2 presents strategies for mitigating these issues.

Manual Fabrication

While large scale manufacturers have addressed many of these challenges, manual fabrication and integration of piezoelectric in other materials remain a challenge. Section 6.3 describes experiments for the manual fabrication of piezoelectric sensors with accessible tools and materials.

Chapter 5

PaperAware: Paper as a Vibroacoustic Material

PaperAware is a collaboration between João Wilbert and Dr. Sanad Bushnaq (KIOXIA Corp.).

5.1 Introduction

Paper is a universal medium that pervades many aspects of our society. Paper has been a rich medium that inspires creation and construction for long. It is also fundamental for communication and expression through literature, art, and design. Paper has been widely explored in Human-Computer-Interaction (HCI) as a low-cost passive medium that can be transformed into an interactive user interface to combine the tangibility of paper with the dynamic nature of software. Steimle (2012) extensively documents this potential.

To make paper interactive, researchers have explored several methods. For example Shilkrot et al. (2015); Nanayakkara et al. (2013); Yang et al. (2012);

Wellner (1994); Makino and Kakehi (2011) make use of external apparatuses such as cameras and touch panels to track interaction. While such an approach that instruments the periphery has the advantage of accurate tracking and real-time feedback using computer vision software, it usually suffers from occlusion and narrow field of view and privacy concerns.

Other methods focus on the instrumentation of the material itself by applying conductive traces on the surface of paper for different sensing modalities. (Olberding et al., 2013; Li et al., 2016; Gong et al., 2014*b*; Wessely et al., 2018).This method seeks to overcome the limitations of camera-based tracking.

Paper instrumentation enables design freedom and uses accessible materials, such as conductive ink, for sensor printing (Gong et al., 2011; Kawahara et al., 2013). Using this method, researchers have demonstrated compelling examples of paper interactivity, such as the work reported by Wessely et al. (2018); Gong et al. (2014*b*); Zhang and Harrison (2018). However, these approaches often require the paper to be permanently modified through printing, coating, or drawing the conductive traces. Prefabrication adds a time-consuming step to apply instrumentation on paper and modification of the paper properties themselves.

Once applied, the sensors become exclusive to that paper only, limiting the reusability of the system. In some cases, such approaches usually require printing over a large area of the paper, limiting the available space for interaction. (Zhang and Harrison, 2018; Gong et al., 2014*b*; Olberding et al., 2013). Besides, it is challenging to apply these methods to existing media that we use in our daily lives, such as newspapers, notebooks, or magazines.

Meanwhile, there are many examples of vibroacoustic sensing in HCI (Cai et al., 2019). Vibroacoustic sensing is used to sense interactions based on surface vibrations, for touch localization (Liu et al., 2017; Paradiso and Leo, 2005; Ishii et al., 1999; Xiao et al., 2014), activity recognition (Laput et al.,

2018) and interaction classification (Lopes et al., 2011; Harrison and Hudson, 2008; Harrison et al., 2011; Ono et al., 2013). In contrast to permanent instrumentation, vibroacoustic sensing has demonstrated successful examples of sensing interaction by attaching and detaching sensors on different surfaces. However, there have been only a few examples that utilize vibroacoustic sensing in the context of paper interactions (Yilei S. Haimo Z. and N.., 2020).

PaperAware is a system that makes standard paper interactive as is by using vibroacoustic sensing. We leverage the vibrations on the paper's surface as a means for sensing interaction. We turn standard paper into an interactive surface when attached on top of four thin piezoelectric sensors, one on each corner of the paper. This ad-hoc approach is non-intrusive to the material, reversible, and is compatible with existing paper. When users interact with the paper, their touch generates vibrations that travel on the paper's surface and reach the piezoelectric sensors on each corner of the paper, as described in Section 4.2.3. The piezoelectric sensors then respond to these vibrations by generating electric signals as an interface to paper vibrations.

We developed a localization technique, Adaptive Received Signal Strength (ARSS), to process these signals and compute the position of the contact point on paper. Our technique adapts to the environment, neutralizes non-idealities in the system, background noise and minimizes the influence of vibration propagation loss and other variables. Since we are using passive vibroacoustic sensing, our system admittedly lacks the ability to detect multi-touch interaction. However, we offer several unique advantages over prior work.

First, no prefabrication or permanent instrumentation of paper is required. Paper instrumentation modifies the paper's material and often involves irreversible prefabrication steps.

Drawing, printing, or coating a paper with sensors limits its reusability once the sensors cannot be transferred or reused in a new sheet of paper.

Second, we use thin-film piezoelectric sensors that occupy a marginal area of the paper; it leaves the user with ample space for interaction. Additionally, our sensors are passive and do not need constant power excitation to function, which may become necessary when we make our system portable.

Third, we support a wide range of rich interactions, including contact-less interactions, such as blowing on the paper's surface.

Fourth, our localization technique is adaptive to the environment, neutralizes background noise, and minimizes the influence of vibration propagation loss and other variables. The accuracy of our localization technique can localize touch with up to 94% accuracy in some regions of the paper. While this may be relatively lower than other techniques, it is still sufficient to enable various paper interactions.

In the following sections, we review prior work, explain our localization technique, describe our hardware and software systems, and introduce the supported interactions. We then present a design space for paper interactions that highlight the currently supported capabilities and outlines a vision for future paper interactions based on vibroacoustic sensing.

Finally, we demonstrate example applications using vibroacoustic sensing to augment paper in the context of communication, music, design, and education.

Our contributions of PaperAware include:

- Leveraging vibroacoustic sensing to enable paper-based interactions, using paper as is, without prefabrication, permanent modification, or using cameras or touch-sensing panels.
- Supporting a wide range of rich interactions, including contact-less interactions, such as blowing on the paper's surface.

- A localization technique that is adaptive to the environment neutralizes background noise and minimizes the influence of vibration propagation loss and other variables.
- Design space and vision for vibroacoustic sensing for interaction with paper, including applications.

5.2 Related Work

5.2.1 Paper Augmentation

Research in HCI has explored paper as an interactive medium to combine the tangibility of paper with the dynamic nature of software (Ishii and Ullmer, 1997). Prior work demonstrates augmentation of paper into a tangible user interface through actuation (Wang et al., 2016; Ogata and Fukumoto, 2015), visual feedback (Coelho et al., 2009; Klamka and Dachselt, 2017; Tsujii et al., 2014; Olberding et al., 2014), power generation (Karagozler et al., 2013) and as an input surface (Zhang and Harrison, 2018; Anoto, 2020; Smartpen, 2020; Makino and Kakehi, 2011; Steimle et al., 2013). Paper has also been explored as a platform for circuit printing (Kawahara et al., 2013) and interactive storytelling (Hershman et al., 2018; Qi et al., 2015; Hodges et al., 2014).

We focus in this section on past research that turns the paper into an input device. We categorize prior work based on where instrumentation occurs in order to enable interactivity. So, we first review work that instruments the environment around the paper, then we take a look at research that instruments the paper itself.

Instrumented Environment

One of the conventional approaches to augment paper interaction is the use of external digital devices embedded in the peripheral environment. This

	Interaction Capability	Sensing Technique	Reusable Material	Requires Fabrication?	User Worn device?	Integration Method	Sensor Type
PaperID (Li, 2016)	Touch, swipe, blow, gesture	RFID	No	Yes	No	Stencil,hand drawn, printed	Passive
Electrick (Zang, 2017)	Touch, swipe	Electric field tomography	No	Yes	Yes (GND)	Coated	Active
PulpNonFiction (Zang, 2018)	Continuous touch, drawing	Electric field tomography	No	Yes	Yes (GND)	Coated	Active
PrintSense (Gong, 2014)	Multimodal	Capacitive	No	Yes	No	Inkjet Printed	Active
Shape Me (Wessely, 2018)	Shape Awareness	Capacitive	No	Yes	No	Inkjet Printed	Active
Cuttable Sensor (Olberding, 2013)	Discrete Touch	Capacitive	No	No	Yes	Inkjet Printed	Active
VersaTouch (Shi, 2020)	Multitouch, continuous touch	Vibroacoustic	No	No	Yes (Transducer)	Attached	Passive
Paper Aware	**Touch, swipe, angle, blow**	**Vibroacoustic**	**Yes**	**No**	**No**	**Attached**	**Passive**

Figure 5.1: Overview on prior work in paper augmentation categorized by capability, technique, sensor re usability, requirement for fabrication, user worn device, integration method and sensor type.

approach uses cameras, depth sensors, or touchpads to track interactions with ordinary paper. Data from cameras is usually post-processed by computer vision algorithms to track interaction and provide real-time feedback through a projector (Holman et al., 2005; Wellner, 1993; Victor, 2020; Bill, 2020; Lee et al., 2008). The advantage of this technique is that it does not interfere directly with the paper's material. However, it can suffer from occlusion and a narrow field of view. Besides, cameras usually need to be fixed at a specific distance, which limits the portability of the system.

Researchers investigate other ways to avoid using fixed external devices and improve the portability of the system. For example, attaching optical sensing devices, such as a miniaturized camera or optical sensors, to either writing instruments or fingers (Shilkrot et al., 2015; Nanayakkara et al., 2013; Yang et al., 2012). Such research sometimes requires printed markers to enhance the device's ability to recognize different material or localize the point of contact in real-time, which makes it suitable for real-time writing digitization, sketching, and note-taking. Several commercial products (Anoto, 2020; Smartpen, 2020; Moleskine, 2020) utilize this approach. However, it sometimes requires the use of special paper compatible with the external device. Moreover, attaching devices on users' fingers limit their mobility and freedom.

Instrumented Paper

Other research propose methods to instrument the paper itself by developing fabrication techniques, or by imbuing sensors directly on the material or paper surface. The research by Zhang and Harrison (2018) proposes a low-cost fabrication method to coat paper with a conductive layer. Other research utilizes electric field tomography to support touch tracking for both finger and writing instruments including pens, pencils, and brush. (Zhang et al., 2017). Meanwhile, Wessely et al. (2018) propose an interactive fabrication method to enable sensing cut patterns in the paper to reflect on digital software. Such a fabrication method uses inkjet-printed capacitive traces used to estimate the length of each trace. Gong et al. (2014*b*) also uses inkjet-printed conductive sensors to create a multi-modal flexible sensing surface in paper to augment everyday objects with flexible sheets. Moreover, Olberding et al. (2013) implements a technique to make paper-printed capacitive sensors robust to various cutting patterns. Li et al. (2016) uses printed, stencil-traced, or drawn passive RFID tags to enable swipe, touch, and motion gestures interactions.

To summarize, prior work demonstrates successful examples of low-cost methods that instrument paper to make it interactive. However, paper instrumentation modifies the paper's material and often involves irreversible pre-fabrication steps. Additionally, once sensors are drawn, printed, or coated, they cannot be transferred to a new sheet of paper, which limits re-usability.

In our paper, we propose acoustic sensing as a technique to preserve the nature of the material by using ad-hoc sensors that can be attached and reused after the paper is used and disposed of. A key advantage of acoustic sensing for touch tracking over other methods is to be minimally intrusive and still afford a rich set of interactions.

5.2.2 Vibroacoustic Sensing in HCI

Acoustic sensing has been one of the significant approaches to tracking a variety of tangible and embodied interaction in HCI.

Interaction Classification

There have been many acoustic sensing techniques that classify a range of tangible interaction modalities Cai et al. (2019). Lopes et al. proposes techniques to detect several types of touch interaction with a single acoustic sensor (Lopes et al., 2011) by combining amplitude analysis and frequency distribution.

Ubicoustics presents a method to characterize and identify daily interaction and activities with acoustic labeling (Laput et al., 2018). Touch & Activate utilizes active acoustic sensing to enable passive objects to detect preregistered tangible interactions by attaching a pair of piezoelectric disks that act as vibration emitted and receiver (Ono et al., 2013).

There is also research that utilizes active acoustic sensing using smartphones to detect finger inputs on a physical surface (Nandakumar et al., 2016), mid-air gestures (Wang et al., 2016) and by adding plastic attachments to phone microphone (Laput, Brockmeyer, Hudson and Harrison, 2015).

On ScratchInput Harrison and Hudson (2008) use the unique sound produced by the fingernail on a surface. They employ an acoustic sensor that can discriminate tap and swipe gestures. TapSense (Harrison et al., 2011) augments touch displays by using acoustic sensing to classify finger, nail, or knuckle taps. Jota et al. (2014) explore the space of foot interactions as an input modality for large displays.

There have been several works that use acoustic sensors to detect interaction with flexible material. For example, Ou et al. (2016) use vibration sensing to capture the direction of scrubbing on hair-textured surfaces.

Other work uses a microphone and other types of sensors to detect interactions with a balloons (Nakajima et al., 2013). Additionally, (Harrison et al., 2011) enables one to encode binary ID into tags as physical notches that for identification through sound scrubbing.

Touch Localization

Prior work demonstrates the use of acoustic sensing for localizing touch or the impact of an object with a planar, rigid surface.

Ishii et al. (1999) uses eight (four on each side) electret pickups attached to a ping pong table and utilizes time difference of arrival to localize the position of the ping ball as it comes in contact with the table surface. Paradiso et al. (2002) utilizes acoustic sensing to detect: touch, taps, or knuckle taps on a large (2m x 2m) glass surface. Xiao et al. (2014) employs acoustic sensing to extended the interactive area of mobile phones and tablets. They report success in resolving the angular position of gestures from finger and writing implements.

On the other hand, Shi et al. (2020) utilizes acoustic sensing for continuous detection of position by utilizing an active transducer attached to the fingertip and three piezoelectric contact microphones. Kim et al. (2018) uses dispersion as a means to detect touch location on a planar surface utilizing the microphones present in mobile devices.

Meanwhile, Pan et al. (2017) uses Time Difference of Arrival (TDOA) of slip pulse waves to perform tap and swipe tracking on multiple surfaces.

Moreover, Liu et al. (2017) proposes a technique to sense touch and discriminate objects in contact with any surface. Finally, Pham et al. (2007) uses the time difference of arrival (TDOA) and location template matching (LTM) to perform continuous tracking of the finger on a surface.

Figure 5.1 shows an overview of methods for sensing interaction with paper, most of the prior that supports discrete touch localization require fabrication of special paper through printing or coating. Additionally, the sensor cannot be reused on a new sheet of paper. Other techniques that have demonstrated multi-touch and continuous tracking of XY position require the user to wear either a transducer on the fingertip or to wear a ground wire.

PaperAware exhibits comparable capability to other methods of instrumentation; however, it overcomes the requirement of imbuing sensors on the paper permanently and enables the same sensors to be re-utilized across multiple paper sheets.

5.3 Sensing Principle

5.3.1 Overview

Source localization is the process of identifying the position of an object within a coordinate system (Djuknic and Richton, 2001; Tong and Zekavat, 2007; Patwari et al., 2005). Source localization is researched extensively to solve many problems in various fields, including mobile communications (Yilin Zhao, 2002), radar (Bahl and Padmanabhan, 2000), as well as Human-Computer-Interaction (Paradiso and Leo, 2005). In our research, successful localization is the cornerstone of enabling paper-based interaction. We use source localization to find the position of the contact point on paper to enable paper-based interaction.

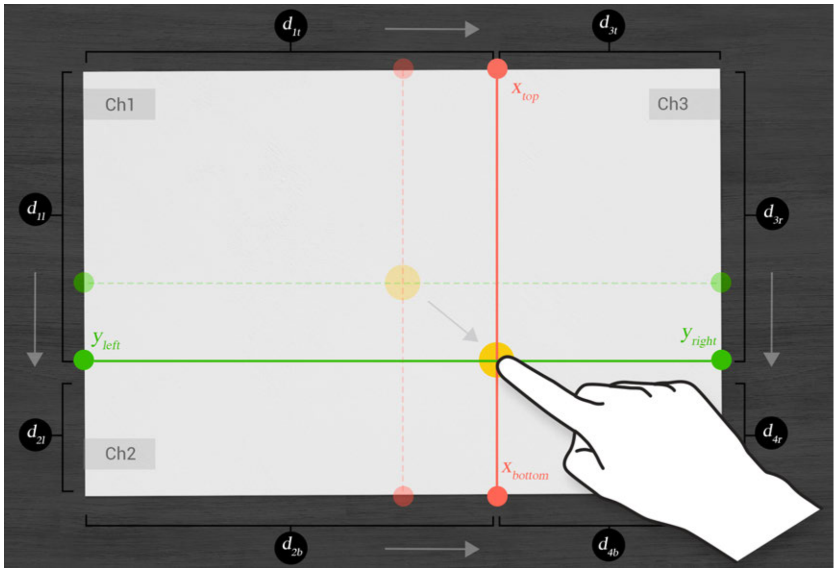


Figure 5.2: Our localization technique allows the system to find the position of the contact point on paper to enable paper-based interaction. Successful localization is essential for enabling paper-based interactions.

Metrics such as accuracy and latency, evaluate the precision of localization. (Barsocchi and Potortì, 2014; Zafari et al., 2019). Accuracy of a localization technique is the error distance between the point where the system calculated the object to be on and the actual point where the object is. Usually, the average error distance is considered (Barsocchi and Potortì, 2014).

Latency is the time it takes the system to identify the object's location. Requirements usually differ by application. For example, localization in video conferencing systems to track an active speaker has lower accuracy requirements than autonomous cars, where localization has a direct effect on passengers' safety on the road.

Localization models can address different requirements and cover a wide range of applications. Commonly used models are Time Of Arrival (TOA), Time Difference of Arrival (TDOA) and Received Signal Strength (RSS) (Reju et al., 2013; So, 2011; Chan and Ho, 1994; Bian et al., 2005; Liu et al., 2020;

Fascista et al., 2018; Martin et al., 2011; Hou and Cui, 2019; Miao et al., 2019). We analyzed these models to find the one that can satisfy our requirements. In our research, we need to localize the users' contact point on paper.

We aim to enable practical paper-based interaction, so it is necessary to achieve accuracy enough to satisfy that goal. Our system must also be practical, such that it functions correctly without relying on heavy calibrations. Besides, the system needs to be robust and adaptive to noise or other nonidealities. After a thorough investigation, we eventually concluded that the best approach is to create our own customized technique based on the RSS model to satisfy our requirements, which is Adaptive RSS. We review next to the commonly used models and explain the reasons behind this decision.

Localization based on TOA and TDOA estimates the contact point's position based on the propagation time of vibrations traveling from the contact point to sensors. Distance is the product of propagation time and speed of vibrations traveling in the paper. TOA and TDOA have high accuracies, so they are used in many applications (Reju et al., 2013; So, 2011; Chan and Ho, 1994). However, since the paper's material or the way it is attached can affect the speed of vibrations, both TOA or TDOA need to have the expected speed in advance to perform calibrations based on that value.

Additionally, TOA technique requires sensors to know the timestamp of the transmitted signal to accurately measure the propagation time (So, 2011), which makes it challenging to use when the source is a passive paper scenario. On the other hand, TDOA is an improved version of TOA that does not require timestamps because it measures the difference in propagation times for waveforms arriving at multiple sensors (Bian et al., 2005; Liu et al., 2020; Fascista et al., 2018).

However, it usually requires all sensors to be well-synchronized, as misalignment between sensors may lead to estimation errors (So, 2011). In some cases, researchers have demonstrated examples that apply TDOA model without the need for sensor synchronization. However, that method still requires a ranging signal to be transmitted from the source periodically (So, 2011), which makes it unsuitable for applications with passive sources.

RSS is another localization model used in applications that have lower accuracy requirements (So, 2011). RSS measures the power of the received waveform and uses it to estimate the contact point's position. The power of the received signal can be represented as (So, 2011):

$$P_i = G_i P_t {d_i}^{-\alpha} \tag{5.1}$$

This equation indicates that there are many parameters affect the received power P_i at sensor i. G_i is the amplification factor of the amplification circuit for signals generated by sensor i. P_t the waveform's original power at the users' contact point on paper at a distance d_i from sensor i. α is the path loss constant, which is the rate at which the signal's power decays over distance. α depends on the propagation environment, such as the paper's material and the way it is attached. So, it is usually difficult, and impractical to precisely know α in advance.

One means of reducing the number of unknowns in equation (5.1) is to use Differential RSS (DRSS) (So, 2011), which is based on measuring the ratio of received power between two sensors. This leads to the following formula:

$$\frac{P_i}{P_j} = \frac{G_i P_t {d_i}^{-\alpha}}{G_j P_t {d_j}^{-\alpha}} \tag{5.2}$$

where P_j is the power of received waveform at sensor j, G_j is the amplification factor of signals generated by sensor j, and d_j is the distance between the contact point and sensor j. Note how P_t is the same for all sensors. Having the same value for all sensors eliminates P_t from the equation because the same source generates vibrations on paper, and all sensors are attached to the same paper. By simplifying and taking the log of both sides, we get to:

$$log(\frac{P_i}{P_j}) = log(\frac{G_i}{G_j}) - \alpha log(\frac{d_i}{d_j}) \quad (5.3)$$

equation (5.3) indicates that there is a linear relationship between $log(P_i/P_j)$ and $log(d_i/d_j)$. If we hypothetically know the exact value of α and sensor gains G_i and G_j, we can find the distance ratio d_i/d_j based on the value of P_i/P_j we measure. The value of d_i/d_j, once calculated, forms one distinct circle on which the contact point must be (So, 2011). We can find the contact point's specific location on the intersection of several circles that result from using multiple sensors.

In reality, however, localization is not that simple. Non-idealities and noise in the environment may result in multiple intersection points between circles, leading to ambiguous results. In addition, it is impractical to precisely know α, G_i and G_j, which are needed to accurately find d_i/d_j. Moreover, we also need to account for factors that cause measurements errors, such as reflections, refractions, and diffractions of signals that result in multiple waveform components that combine either constructively or destructively at the sensor (So, 2011). Other factors include mismatches in amplification gains between sensors, which lead to measuring inaccurate power ratios. Additionally, we need to keep in mind that random environmental factors, such as surface vibrations under the paper and background noise in the room, also affect the measurement's accuracy of the measurement. That is why RSS and DRSS usually depend on statistical models and approximations to account for these random variables, or they resort to manual calibration or pre-training that collects patterns to estimate locations (So, 2011). We developed ARSS to address these issues, as we explain next.

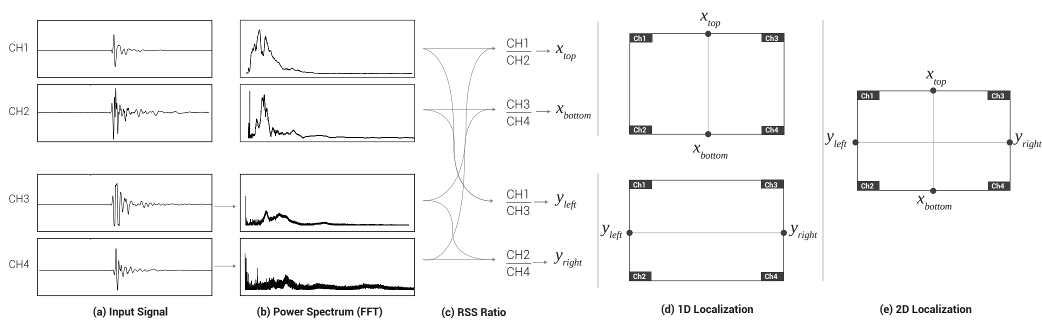


Figure 5.3: Adaptive Received Signal Strength (ARSS) localization technique. We calculate the x and y coordinates of the contact point by taking the power ratio between channel-pairs on each edge of the paper. Our localization point is the intersection of the horizontal line between x_{top} and x_{bottom}, and the vertical line between y_{left}, y_{right}.

5.3.2 Adaptive Receive Signal Strength

In this section, we explain the concept of the technique we use in our system for localization.

The ARSS technique we developed is based on the RSS model. So in principle, we measure the power of the received waveforms and use it to estimate the position of the contact point on paper. However, instead of estimating the contact point's location by intersecting circles, which may cause ambiguities, we intersect lines. We are leveraging the fact that we are localizing contact points in a confined space, which is the paper's surface only to approximate the contact point's position. We calculate the x and y coordinates of the contact point separately by taking the ratio of power between channel-pairs on each edge of the paper to find x_{top}, x_{bottom}, y_{left}, y_{right}, as shown in Figure 5.3. We then do 1D localization by forming a horizontal line between x_{top} and x_{bottom}, and a vertical line between y_{left}, y_{right}. As a result, the intersection point of these two lines becomes our desired 2D localization. We take this approach to overcome the shortcomings of the conventional RSS model discussed in the previous section.

The price we pay for following this approach is losing some accuracy. However, this approach allowed us to make our technique adaptive to the environment and non-idealities in the system. It also minimizes the influence of vibration propagation loss and other variables. Besides, it does not require statistical models, pre-training, nor extensive calibration. Moreover, this approach made our localization more straightforward and more practical. Admittedly, our system cannot detect multi-touch interaction since we are using passive vibroacoustic sensing. Nevertheless, we experimentally measured an accuracy up to 94%, which makes it practical for our design space and applications, as we detail later in the paper.

To explain the concept behind our ARSS, consider the case where we have four sensors attached to a paper, as shown in figure 5.4. Each sensor is connected to a circuit to amplify its output and connected to an audio interface.

The audio interface receives signals generated by all sensors, with each arriving on a separate channel. We name the channel of sensor S1 on the top left corner of the paper CH1, channel of sensor S2 on the bottom left CH2, channel of sensor S3 on the top right CH3, and channel of sensor S4 on the bottom right CH4. A computer and audio interface samples and processes all four channels in real-time. Finally, our software back-end computes the Fast-Fourier-Transform (FFT) for all channels to measure their total power and perform the localization.

As we explained previously, we calculate the position of the contact point by finding its coordinates on each edge of the paper. For example, we find the x_{top} coordinates on the upper edge of the paper by taking the power ratio between CH1 and CH3. In this case, equation (5.3) becomes:

$$log(\frac{P_1}{P_3}) = log(\frac{G_1}{G_3}) - \alpha log(\frac{d_{1t}}{d_{3t}}) \tag{5.4}$$

where P_1 is the power of CH1, P_3 is the power of CH3, G_1 is the amplification factor of S1, G_3 is the amplification factor of S3, d_{1t} is the distance between x_{top} and S1, d_{3t} is the distance between x_{top} and S3, as shown figure 5.2. Assuming an ideal scenario in which G_1 is equal to G_3, when measurement shows that P_1 is equal to P_3, it means d_{1t} is equal to d_{3t}. In that case, x_{top} would be precisely in the middle between S1 and S3.

This is considered the ideal starting position, which indicates that either there was no contact on paper or there was contact on the middle of the paper. When P_1 is higher than P_3, then d_{1t} is smaller than d_{3t} and x_{top} is near to S1 rather than S3, which indicates x_p coordinates of the contact point is closer to S1 rather than S3. Finally, when P_3 is higher than P_1, then d_{1t} is larger than d_{3t} and x_{top} shifts toward S3. We use this concept to find x_{bottom} on the bottom edge between CH2 and CH4, y_{left} on the left edge between CH1 and CH2, and y_{right} on the right edge between CH3 and CH4, as explained in figure 5.3. Our localization point is the intersection of the horizontal line between x_{top} and x_{bottom}, and the vertical line between y_{left}, y_{right}.

In practical scenarios, however, the above discussion faces two obstacles. First, G_1 and G_3 is never guaranteed to be precisely equal in practice, and they suffer from shifts due to non-idealities in the circuit. This means x_{top}, x_{bottom}, y_{left} and y_{right} will suffer from unpredictable shifts. Second, prior knowledge of α is required in order to calculate find the points on each edge of the paper-based on equation (5.3), and it is usually impractical to precisely know α that depends on the paper's material and attachment, as discussed before. However, we overcome these obstacles by making our technique adaptive. Our technique adapts to the environment, neutralizes non-idealities in the system and background noise, and minimizes the influence of vibration propagation loss and other variables.

Once our system powers on, we expect each of x_{top}, x_{bottom}, y_{left} and y_{right} to be ideally in the middle of its corresponding edge until users touch the paper. So, if our system detects a shift in any of these points due to non-idealities or noise, it automatically corrects that shift by estimating the amount of shift and adding it to the calculations at startup. In other words, equation (5.3) becomes:

$$log(\frac{P_i}{P_j}) = log(\frac{A_i G_i}{A_j G_j}) - \alpha log(\frac{d_i}{d_j}) \tag{5.5}$$

A_i and A_j represent the correction factors the system applies for signals generated by sensors i and j, respectively, to force the ratio P_i/P_j = 1 on startup in order to guarantee the intersection point between the horizontal and vertical lines to be exactly in the middle of the paper. The system then uses the recorded values of A_i and A_j in all subsequent calculations until it powers off. Users can also manually re-calibrate the system by simply pressing one button on the keyboard to send a calibration request to the system.

By following this approach, the system automatically adapts to misalignments in the circuits' amplification and random environmental factors, such as static surface vibrations under the paper and background noise in the room. Moreover, dynamic noise in the environment that may occur during the system's operation will affect all sensors, and therefore will be mostly canceled-out, thanks to the fact that we are looking at the ratio between each sensor-pair.

Meanwhile, getting our system to adapt to the environment on startup has another valuable advantage. Since each coordinate point on each edge of the paper will be in its ideal position on startup thanks to the applied correction, we can now work around the need to precisely know α in advance by touching the paper once on each sensor. This enables us to know the expected maximum and minimum values of the ratio of P_i/P_j between each sensor-pair. We use these values to map the distance ratio of d_i/d_j to the paper's actual dimensions.

5.4 System Setup

In this section, we describe the system setup of PaperAware.

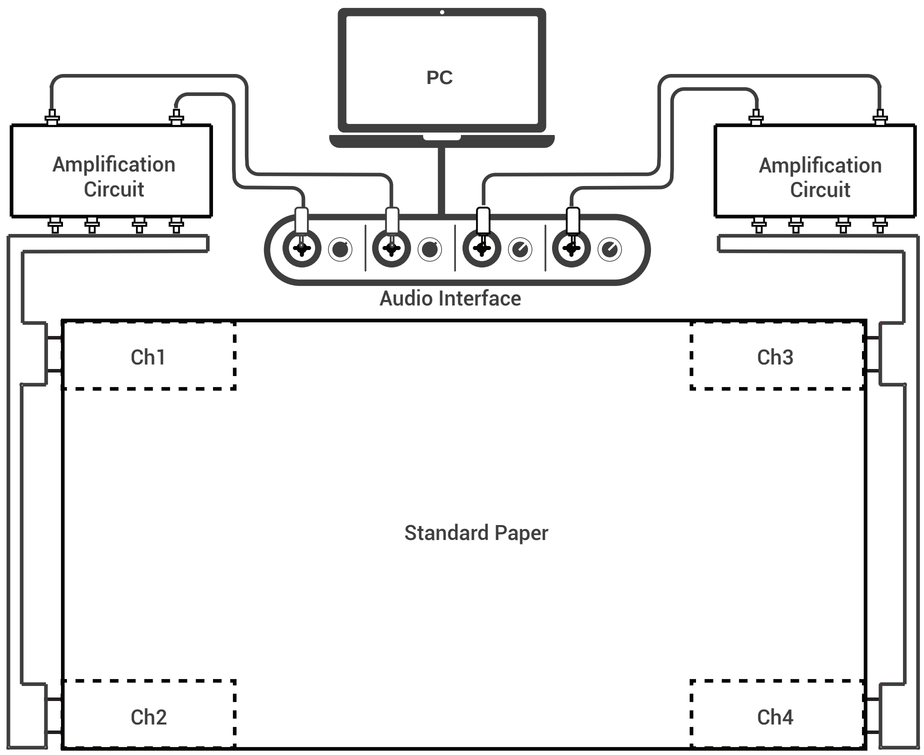


Figure 5.4: System setup of PaperAware. Each sensor is connected to an amplification circuit and an audio interface. The audio interface sends all channels to a computer to be sampled then processed in real time. Our software back-end computes the fast-fourier-transform (FFT) for all channels in order to measure their total power and perform the localization.

5.4.1 Piezoelectric Sensor

During the development of PaperAware, we selected and characterized two types of piezoelectric sensors. One of the transducers consists of the piezoelectric ceramic disk commonly used for vibroacoustic sensing applications. The disk is metallic circular transducer coated with a layer of lead zirconate titanate (PZT). We characterized the frequency response of the disk with an impedance analyzer to find the resonant and anti-resonant frequencies of the piezoelectric material.

Figure 5.5 contains a plot of piezoelectric disk impedance. The resonant and anti-resonant frequency of the disk appear around 100kHz of frequency. At frequencies in around 1kHz we observe the high pass characteristic the piezoelectric transducer.

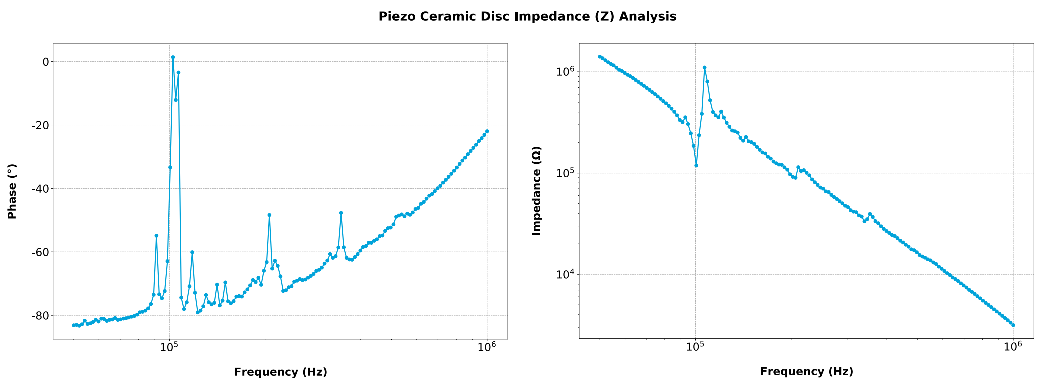


Figure 5.5: Plot of ceramic piezoelectric transducer impedance (Z). *Left:* Impedance in ohms as function of frequency. *Right:* Phase as function of frequency.

We characterized a 28 μm PVDF thin film from TE Connectivity. Figure 5.6 shows an impedance analysis of this sensor. Given the compliance and flexibility of the PVDF thin film it does not exhibit the same sharp resonance (mechanical and electrical) as the piezoelectric disk. It exhibits lower impedance (hence, a higher efficiency) at frequencies in MHz range, an advantage that can be leveraged in future work. For our purpose, the piezoelectric thin film's compliance was an essential factor for its selection as a sensor for our system. Hence we use four 12 μm thin-film piezoelectric sensors from TE Connectivity.

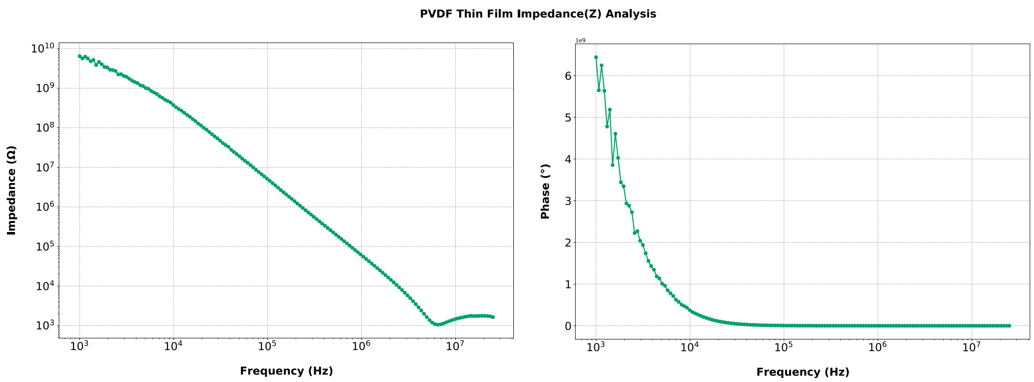


Figure 5.6: Plot of piezoelectric thin film impedance analysis (Z). *Left:* Impedance in ohms as function of frequency. *Right:* Phase as function of frequency.

5.4.2 Amplification Circuit

Circuit Design

We designed the amplification circuit from the grounds up. The conditioning circuit for PaperAware has the following objectives:

- Mitigate environmental noise and parasitic capacitance induced by the piezoelectric sensor.
- Compensate for the difference in voltage response from each sensor.
- Physical robustness to constant manipulation of sensors.
- Output both analog and digital signals.
- Receive power from a standard 5V single supply source.
- High input impedance for use with piezoelectric sensor.
- Amplify the transducer signal to a maximum 100x in gain.

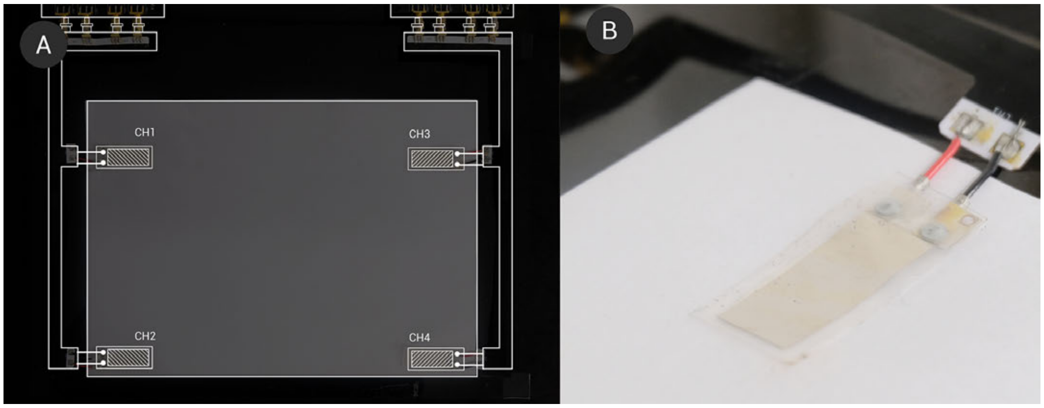


Figure 5.7: Image with top view of the PaperAware setup. *Left:* Diagram highlights position of sensors on paper. *Right:* Close up of TE Connectivity piezoelectric thin film.

Our final circuit design consists of a two-channel, 2-stage amplifier with a high pass filter and analog output powered by a 5V power source. Each channel of the board uses an Analog Devices AD8221 instrumentation amplifier with a gain between 1x and 10x that set by a variable resistor. As input protection, we utilize a 10MΩ resistor across the input pins of the AD8221 and a 1MΩ resistor between the negative input pin of the amplifier and the bias voltage. We use the instrumentation amplifier due to its performance in common-mode rejection.

In the first stage, we bias the input signal to 2.5V to make use of the full amplitude of the charge generated by piezoelectric material. The second stage uses Texas Instruments TLV2374 quad OP-AMP. We use the first channel from the TLV2374 to bias the input signal on the firsts stage. In the second quad OP-AMP channel, we implemente a 2^{nd} Order high-pass Sallen Key filter with a cut off frequency of 200Hz. We designed the filter using the Analog Devices filter design tool. The third channel from the TLV2374 adds a second gain stage with a maximum gain of 10X. The fourth channel of the TLV2374 buffers the output and scales the signal from 0V-5V to 0V-3.3V with a voltage divider. The output signal from the amplification stage of the circuit connects to the ADC pin of a Atmel SAMD11 microcontroller for

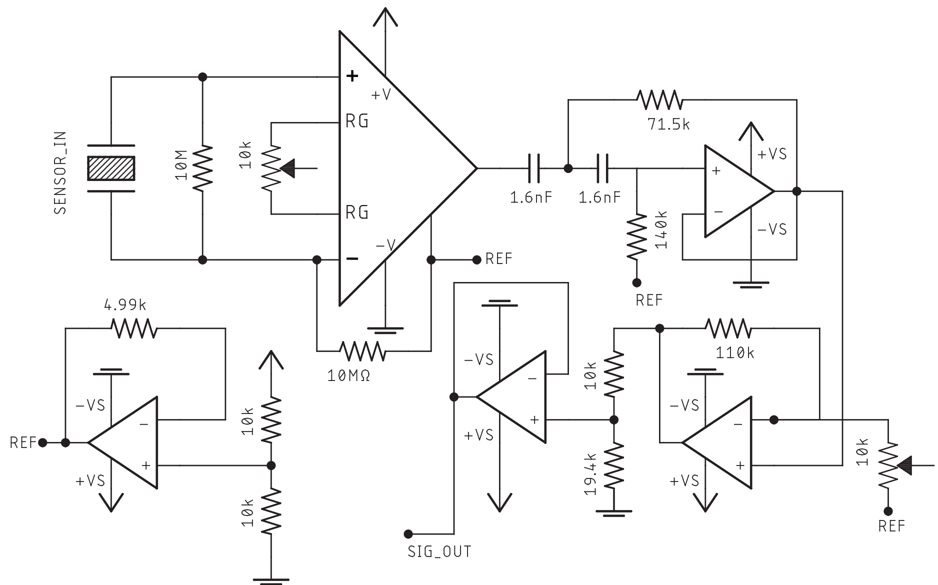


Figure 5.8: Schematic of one-channel of PaperAware signal conditioning circuit.

signal conversion and data processing in future versions.

In the current version of PaperAware, we bypass the microcontroller and output the analog signal to a 4-channel Bheringer UMC404HD audio interface that samples the audio signal at 192kHz. Figure 5.8 shows the schematic of a single channel of our conditioning circuit.

Each PCB board contains two channels based on the schematic mentioned above. The board consists of a two-layer PCB with a ground plane on the top layer and SMB connectors for sensor input and signal output. (Figure 5.9).

5.4.3 Circuit Characterization

Figure 5.11 and 5.12 show transfer function of our conditioning circuit. We characterized the circuit utilizing a Digilent Analog Discovery 2 Network Analyser with a sinusoidal sweep with 1V amplitude, 2.5V bias, a start fre-

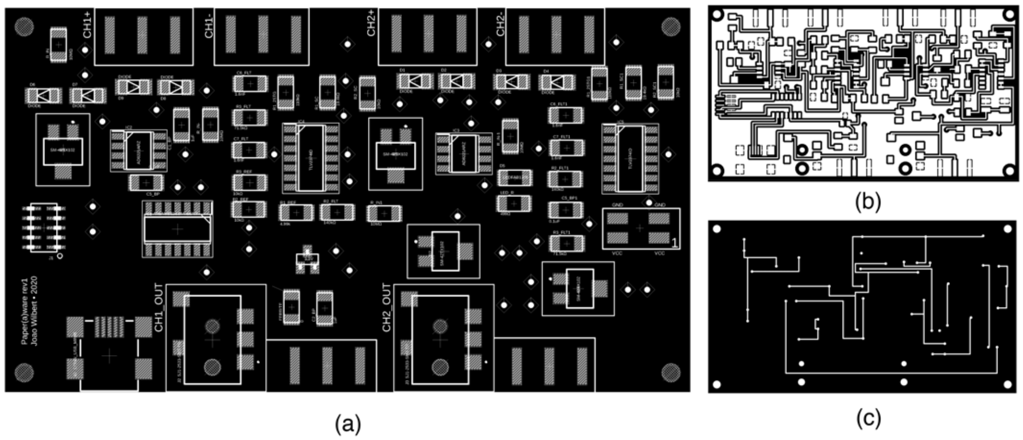


Figure 5.9: *(a)* PCB layout with component placement *(b)* PCB top layer *(c)* PCB bottom layer

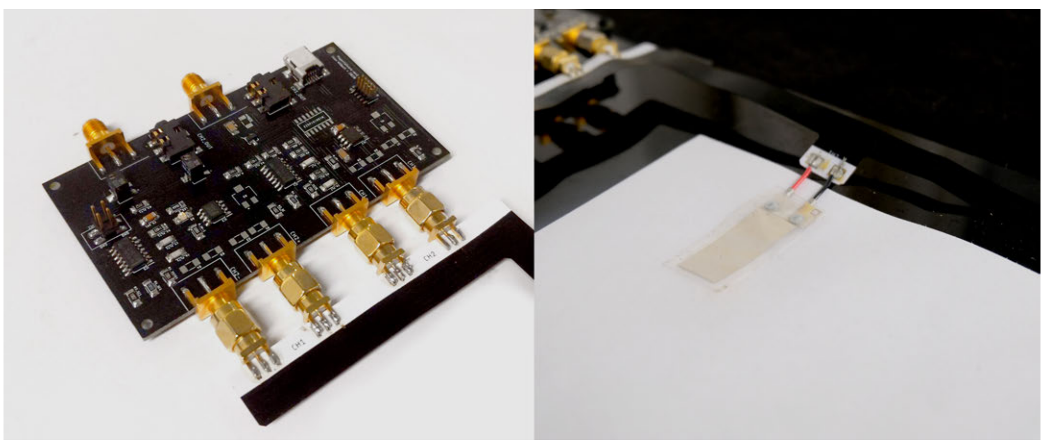


Figure 5.10: Image of PaperAware setup *a.* Top view of hardware setup. *b.* Closeup image of piezoelectric thin film sensor.

quency of 50 Hz, and a stop frequency of 20KHz with 151 steps.

Figure 5.13 shows the output from the amplification circuit to the audio interface. Touching the paper near the sensor on CH1 shows a peak with higher amplitude than CH2. Touching near the sensor on CH2 shows a waveform which a higher amplitude than CH1. Touching the middle point between sensors we observe waveforms with similar amplitudes.

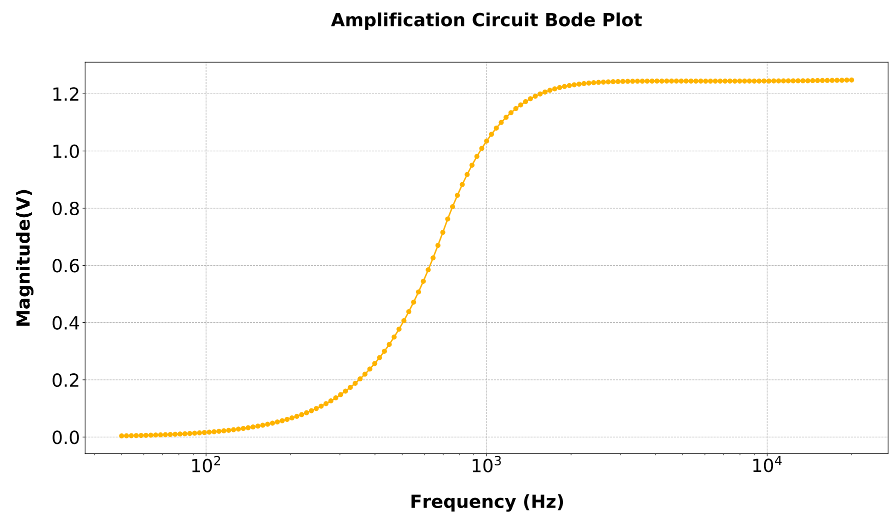


Figure 5.11: Bode plot with transfer function from PaperAware circuit with Magnitude (V) as function of Frequency (Hz).

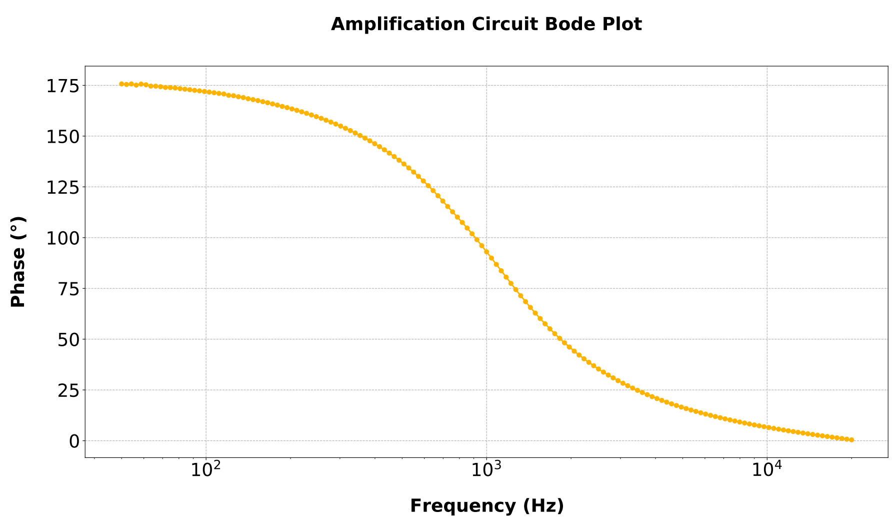


Figure 5.12: Bode plot with transfer function from PaperAware circuit with Phase as function of Frequency (Hz).

5.4.4 Connection Strategy

Each sensor is attached to a corner of the paper using double-sided adhesive tape. The four sensors are connected to the readout electronics by a

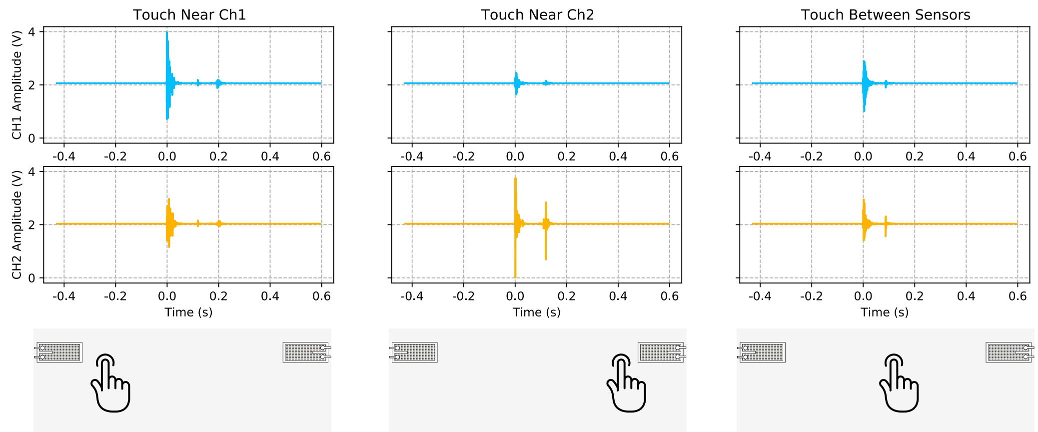


Figure 5.13: Waveform resulting from touch gesture performed next to each channel and in between the sensors.

pair of custom-designed flexible connectors, as shown in Figure (5.10).

The flat flexible connectors are shielded with ground planes on the top and bottom to help reduce noise and shield the signal from parasitic capacitance. These are connected to the circuit using SMA connectors, as shown in Figure 5.7.

The custom connector is made of seven layers. The top and bottom layers consist of coverlays and solder points that expose the contacts to the piezoelectric sensor. The layer under the coverlay is a ground plane connected to the ground of the amplification circuit via the SMA connector. A polyimide film insulates the ground plane and the inner copper traces that connect the sensors to the input pins of the circuit.

The connector positions the sensors in fixed points on a plane and provide robust shielding from environmental noise or capacitance induced by the user's hands when manipulating the paper.

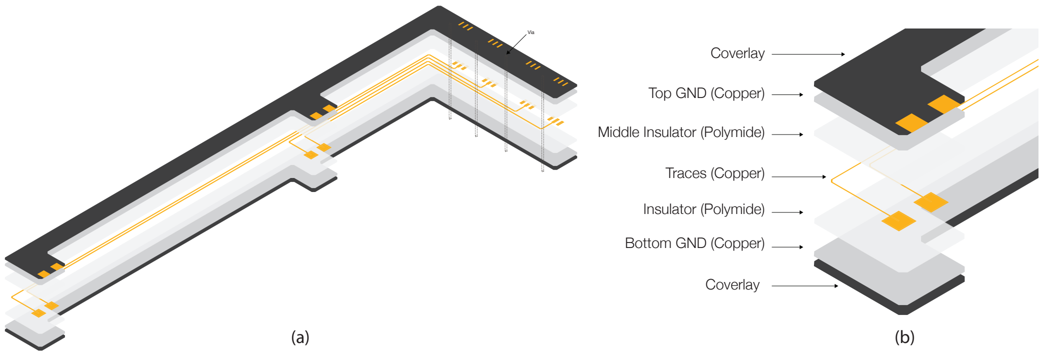


Figure 5.14: Diagram of connection strategy between piezoelectric sensor and conditioning circuit. *(a.)* Exploded diagram of flexbile connector *(b.)* Close-up with layer breakdown of flexible connector.

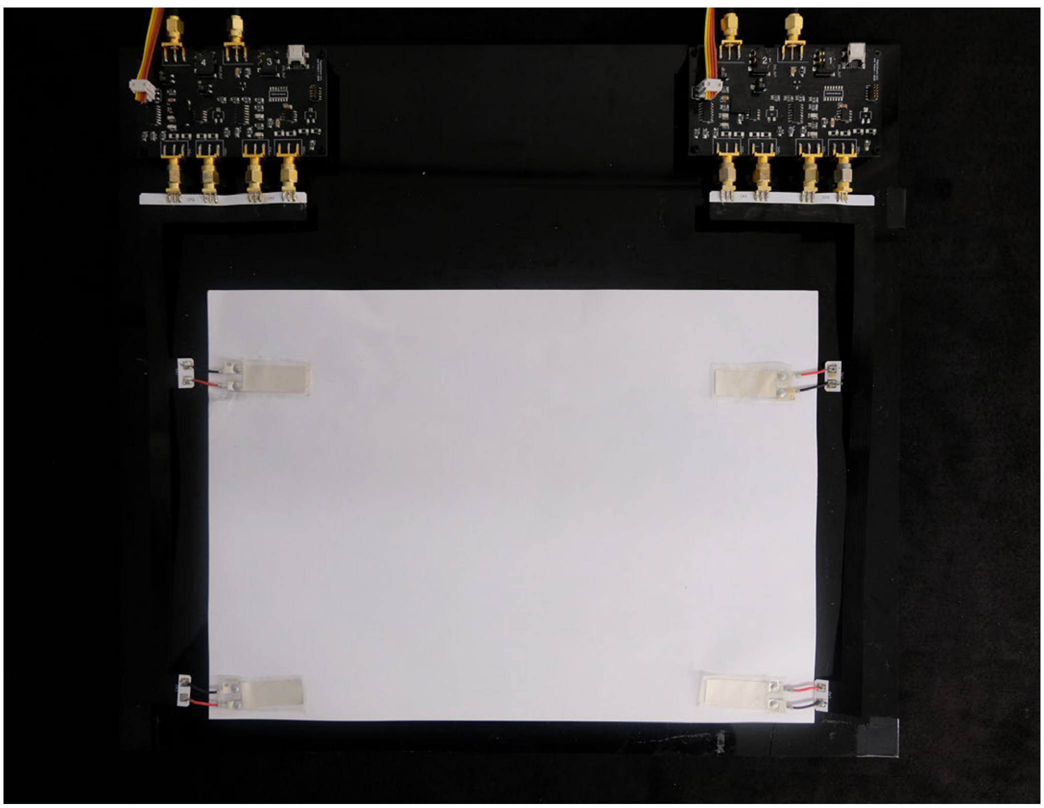


Figure 5.15: Top view image of hardware setup for PaperAware

5.4.5 Software Interface

On the backend, we implement a custom software pipeline to read the sampled signals in all four channels simultaneously and process it in real-time. Our software pipeline is implemented in C++ using OpenFrameworks (OpenFrameworks, 2020). We compute the Fast-Fourier-Transform (FFT) of all channels using the popular library Maxim(Grierson, 2020).

In our software interface, once system powers on, it calculates the initial positions of x_{top}, x_{bottom}, y_{left} and y_{right}. Based on the positions for x and y axis, we compute the intersection point between the axis. We can detect the XY position of touch by drawing a tangent line between the center point of the paper and the current intersection of x and y axis, as shown in Figure 5.16.

Figure 5.16: Screen capture from interface touch location in three distinct positions. Red circles refer to x_{top}, x_{bottom} positions. Green circles refer to y_{left} and y_{right} positions. Cyan circle refers to the intersection between $_x$ and $_y$ axis. Yellow circle refers to position where touch was detected.

Using this system and the ARSS sensing principle as a basis, we implement a series application level algorithms to locate XY position in real-time and support multiple interaction primitives including discrete touch, swiping, and touch angle estimation.

5.5 Evaluation

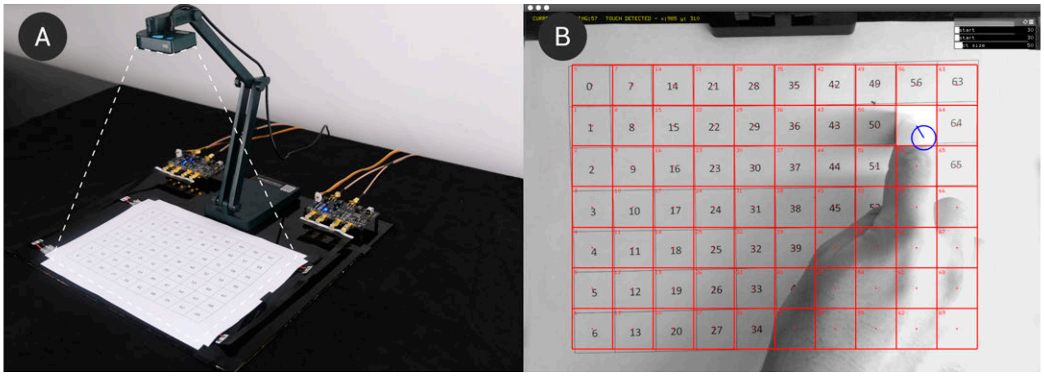


Figure 5.17: Technical evaluation experiment. (a) PaperAware setup with printed test sheet aligned with overhead camera (b) Evaluation software displaying view from camera and alignment between printed test sheet and software grid.

To evaluate the accuracy of our localization algorithm, we designed an experiment using a printed sheet with 69 squares. The sheet was attached to our sensing hardware fitted with an overhead camera, as shown in 5.17. We created a custom evaluation software with the same number and dimension of squares from the test sheet. We connected the evaluation software to our ARSS technique to receive localization information. Once ARSS detects a touch and localizes its position, it sends the information to the evaluation software.

The evaluation software then computes the localization accuracy by calculating the difference between the localized position of the touch and its actual position. We use this difference to calculate two metrics, the RMS error from the localized position of the touch and its actual position and an estimated accuracy based on that value.

Figure 5.18 illustrates our logic for calculating RMS error and accuracy in the test setup.

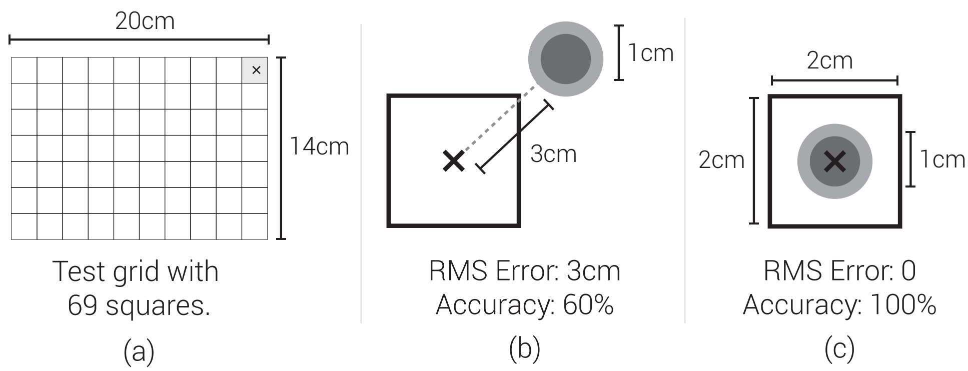


Figure 5.18: Diagram with measurements of test squares. Each square cell is 2.0cm x 2.0cm. Total grid dimensions: 20.0cm x 14.0cm. Printed on A4 paper sheet (21.0 x 29.7cm)

We assume that radius of a finger touch measures approximately 1cm based on the reported average diameter of fingertips. For each of the 69 squares (Figure 5.18.A). When the system detects a touch gesture, we use Euclidean distance between the center of the test square and the location of touch estimated by our system to calculate the root-mean-squared error (RMS). For example, a touch gesture outside the center of the test square by 3cm the RMS error is 3cm (as shown in Figure 5.18.B). In the hypothetical case of a touch occurring precisely at the center of the test square the RMS is zero therefore the accuracy is 100% (as shown in Figure 5.18.C). The accuracy is calculated based on the error distance, as shown in the following formula:

$$Accuracy = (1 - \frac{|d_{ideal} - d_{measured}|}{d_{ideal}}) * 100\% \tag{5.6}$$

d_{ideal} is the ideal position of the touch for each square, and $d_{measured}$ is the localized position by our technique for that square. We estimated d_{ideal} to be around 1 cm, based on the reported average diameter of fingertips. Figure 5.20 shows our accuracy measurement setup. We used a top view camera with a video feed to do this experiment. The blue circle refers to the touch position estimated by our system, and the blue line is the distance between

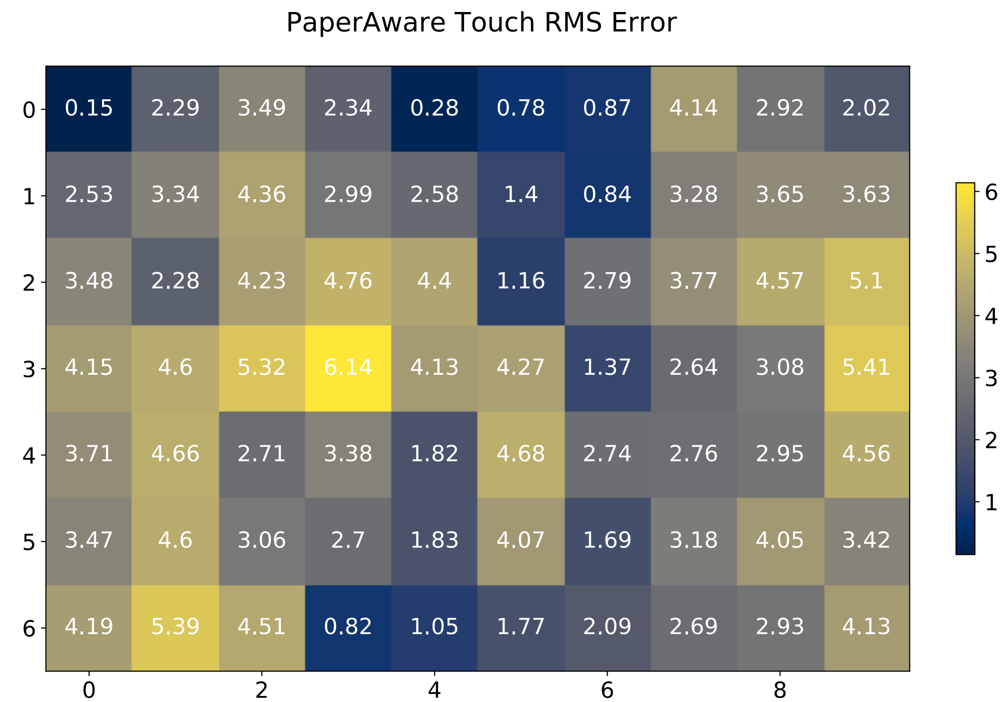


Figure 5.19: Plot displaying RMS error in cm 69 locations printed on paper surface during our technical evaluation experiment. Each square cell is 2.0cm x 2.0cm.Total grid dimensions: 20.0cm x 14.0cm.

d_{ideal} is the ideal position of the touch for each square and $d_{measured}$. We took our measurements by touching each square on the paper and recording the result based. We repeated the experiment over 20 times for each square on the paper, then took the average. With this system we generated two plots: Figure 5.19 which plots the RMS error in centimeters and Figure 5.20 that plots accuracy estimation based on formula 5.6.

The results highlight that error is lower on edges where accuracy can reach up to 94%. Results also show that error increases as we move towards the middle of the paper. While the accuracy drops to 67% in some locations, this is still considered a good enough accuracy for our research purposes, as it allowed us to successfully implement many paper-based interactions, as we detail later on in this paper.

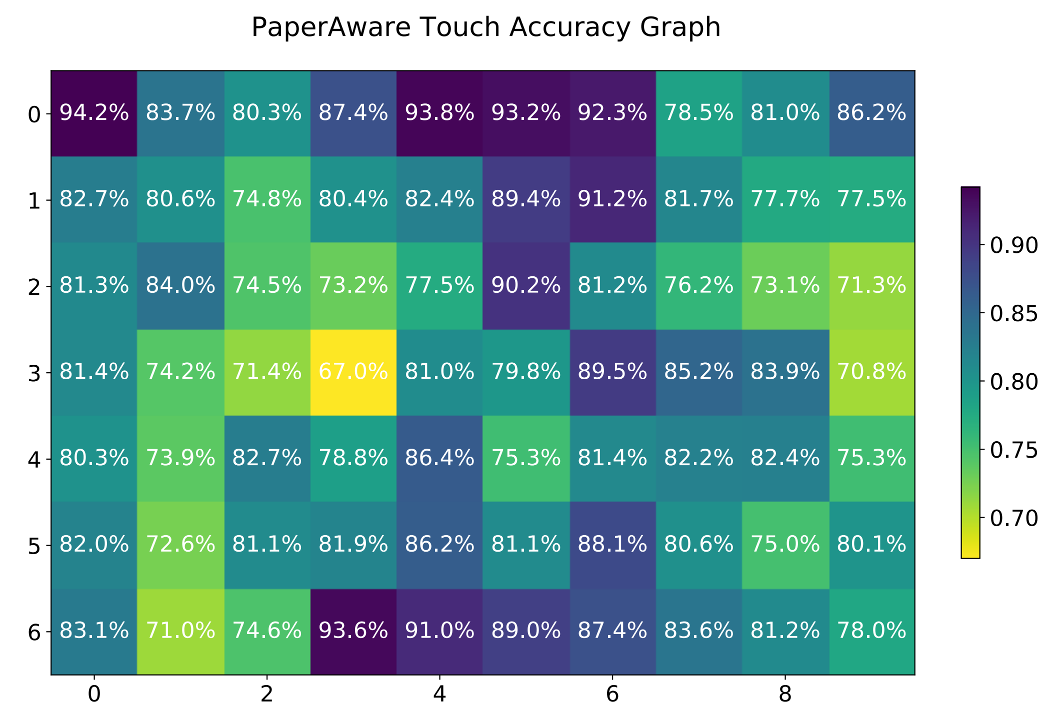


Figure 5.20: Plot displaying estimated accuracy based on Equation 5.6 on 69 locations printed on paper surface during our technical evaluation experiment. Each square cell is 2.0cm x 2.0cm.Total grid dimensions: 20.0cm x 14.0cm.

5.6 Touch Interactions

5.6.1 Discrete Touch

We can achieve discrete touch tracking in the X and Y axis by combining the calculated center point of the vertical (y_{left} and y_{right}) and horizontal (x_{top} and x_{bottom}) axis as described previously. Our system can detect the location of the touch and reflect that on software.

5.6.2 Horizontal/Vertical Swipes

When changed to swiping mode, our system can detect the gesture position in the vertical and horizontal axis, as shown in Figure 5.22. This is possible

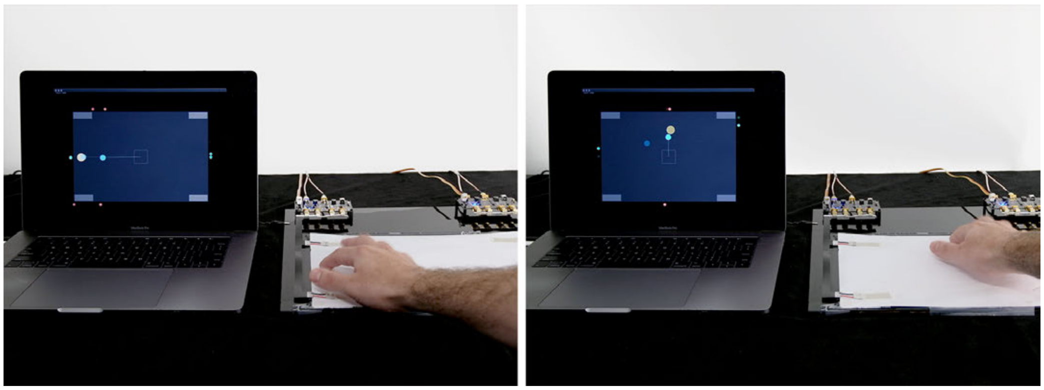


Figure 5.21: Image showing detection of XY touch on paper surface.

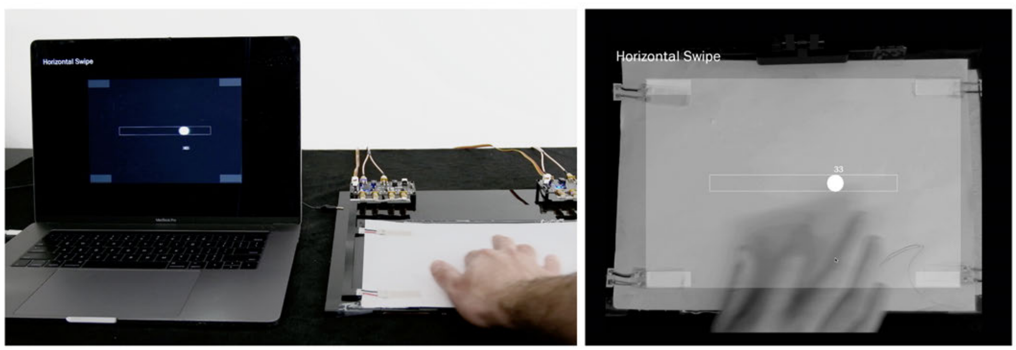


Figure 5.22: Image showing swipe gestures on paper surface.

by leveraging the discrete touch localization while using one only degree of freedom on the paper. For instance when tracking horizontal swipes we utilize the displacement of center point of x_{top} and x_{bottom}, consequently for vertical swipes we use y_{left} and y_{right}. Enabling swiping gestures allows the paper to become a tangible input to digital system. Enabling the mapping of tangible actions to adjusting sliders, faders, and knobs. In this scenario paper is instantly interactive and becomes controller to digital interfaces.

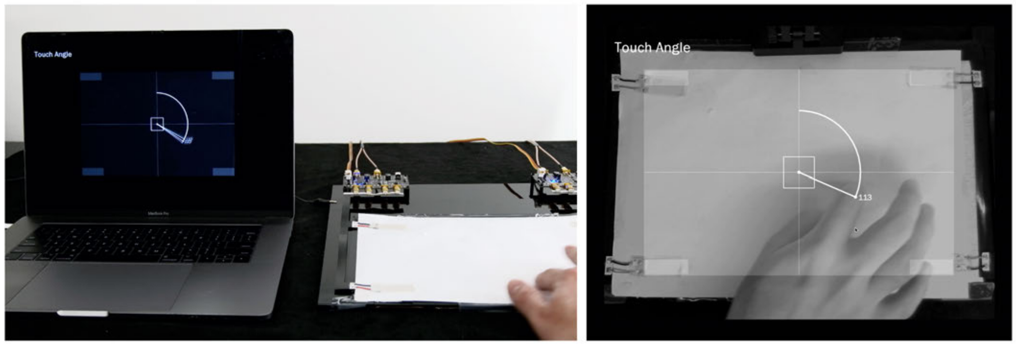


Figure 5.23: Image showing detection of touch angle on paper surface

5.6.3 Touch Angle

To estimate track touch angle on paper (Figure 5.23) we utilize the center point of the two axis (x_{top}, x_{bottom},y_{left},y_{right}) concurrently. Given the location in XY, we compute a tangent line that starts at the center of the paper and reaches target the XY point. To calculate angle we compute the angle in degrees from the XY in relation to a reference point normal to the X axis of the paper. As the finger runs through the paper causing a continuous vibration stream we can track the rotation event in real time. In the context of applications, this allows paper to be a tangible controller for digital interactions and UI elements as rotary dials and encoders.

5.6.4 Vibration Direction

Vibration detection is a non-contact interaction that is unique to vibroacoustic sensing, as shown in Figure 5.24. In this example, we utilize the ARSS technique and combine the touch angle estimation with XY location to determine the direction and position of the vibration source. This source can be generated either by blowing on the paper surface or other devices that can emit a vibration, such as a speaker or handheld fan. In Figure 5.24 we visualize the vibration direction using vector field. The estimated XY

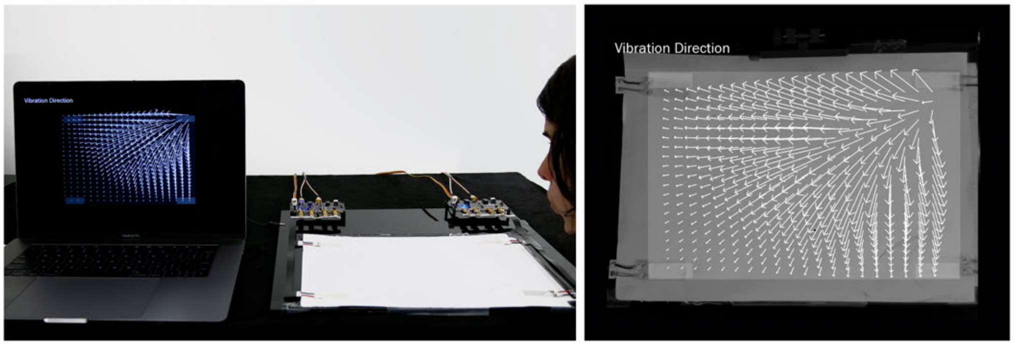


Figure 5.24: Image showing paper generating vector field based on blowing direction on paper.

position defines the direction of the vectors in the field.

5.7 Design Space

Based on vibroacoustic sensing, we propose a four-dimensional design space for paper as an interactive interface. This design space expands on interaction primitives presented.

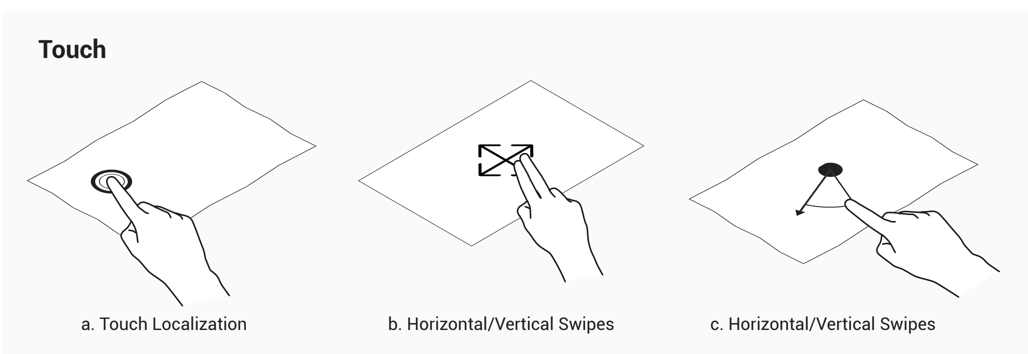


Figure 5.25: Diagram of currently supported touch interactions on paper

Beyond the touch interactions implemented as illustrated in Figure 5.25 we present a vision in which touch location is combined with activity recognition to enable plentiful space of interactions in which paper can sense the interaction with other instruments, aware of its current state, shape and able to sense forces from its surroundings. We propose that the technique of vibroacoustic sensing can be applied to a broader range of flexible, sheet-like material, increasing the latitude of possible use cases and interactions.

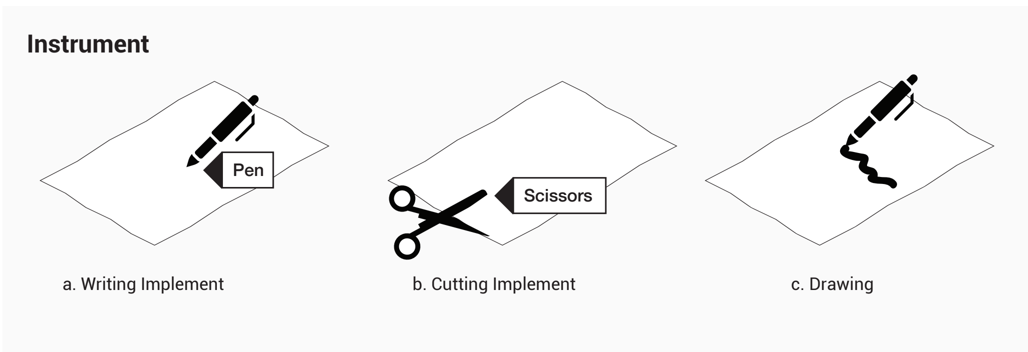


Figure 5.26: Diagram that shows detection of interactions with the material.

For instance, vibroacoustic paper could discriminate physical writing implements (pen, sharpie, pencil, chalk) as they come in contact with the surface of the paper to trigger corresponding changes in texture, a brushstroke of digital counterparts (Figure 5.26.a). By combining positional sensing with interaction classification, vibroacoustic paper may be able infer user intent and activity such as drawing, sketching, writing, doodling (Figure 5.26.b) Additionally machine learning models used for sketch and drawing classification can recognize users input in real-time (Figure 5.26.c).

Another example is to track the cutting path of scissors and other cutting instruments, enabling real-time correspondence between physical material and digital model (Figure 5.27.a). Other interactions may include: sense folding patterns, tearing, stacking, rolling (Figure 5.27.b) that can be mapped

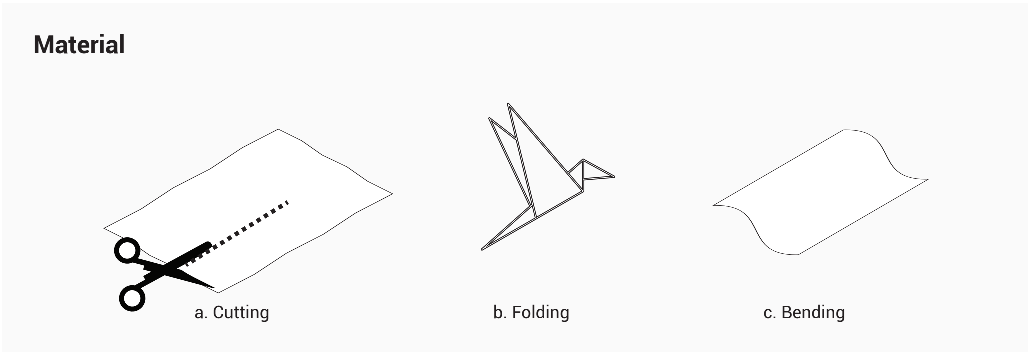


Figure 5.27: Diagram of design space vision in which interaction with paper as a material can be inferred.

to digital actions such as organizing, deleting, archiving (Figure 5.27.b)

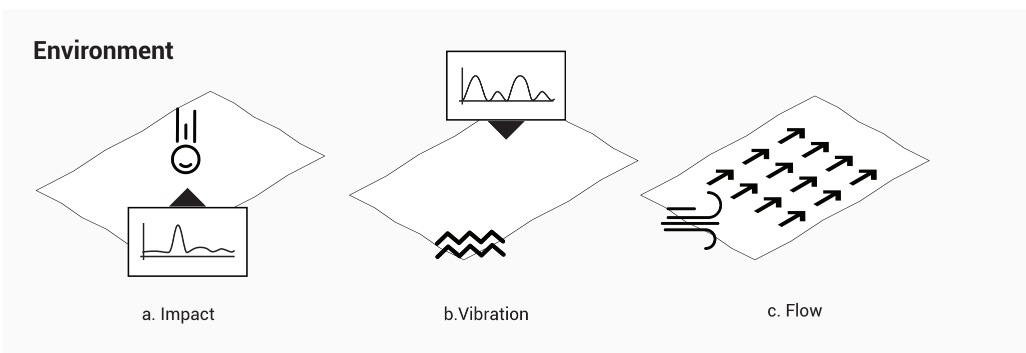


Figure 5.28: Diagram of design space vision that shows interaction of paper with the environment.

Ultimately, sheet-like material can become a sensor for physical interactions with other elements from the environment, leveraging the planar, thin, and flexible sheet material qualities. These interactions include, sensing the impact of an object with a large flexible surface (Figure 5.28.a), localize the source of vibration (Figure 5.28.b) track speed and force distribution vectors along a surface (Figure 5.28.c).

5.8 Applications

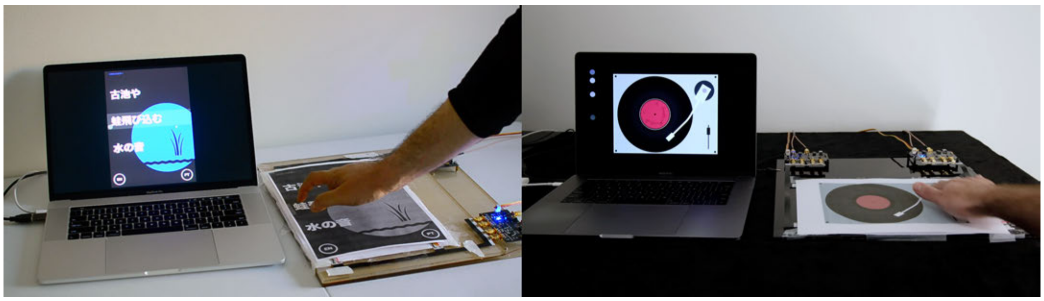


Figure 5.29: Image of PaperAware application demos *Left:* Printed poster augmented with vibroacoustic sensing can translate text based on touch position. *Right:* Printed record player on paper media enables the user to scratch records and hear sound output.

5.8.1 Instant Augmentation of Print Media

Touch to Translate Poster

This example demonstrates the augmentation of paper with functionality for accessibility or real time translation of printed content. To interact, the user touches on the text printed on the paper the hear the translation of that text through a set of speakers. (Figure 5.29 *Left*). This application demonstrates the instant augmentation of ubiquitous paper media (posters, books, magazines) with digital information without requiring the media to be modified in advance.

Paper Record Scratchin'

In this application, by swiping vertically, the user controls the player's playback speed, enabling the record to be 'scratched' back and forth. The scrubbing interaction corresponds to scratching music as it plays through the computer speakers. The speed of the gesture determines the pitch of the sound similar to the sound of scratching a real vinyl record (Figure 5.29

Right).

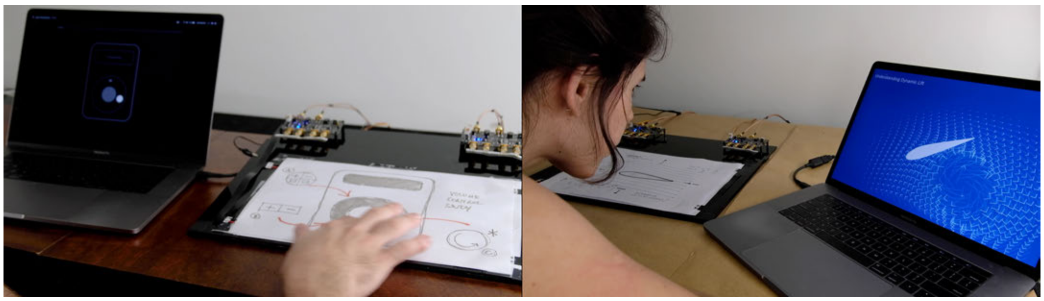


Figure 5.30: Image of PaperAware application demos.*Left:* Application that shows paper responding to vibration as part of an interactive exercise sheet.*Right:* Example of paper being used to prototype interactive gestures with a digital platform in real time.

5.8.2 Prototyping and Learning

Blow Based Airflow Simulation

This example presents an aerodynamics textbook that visualizes how wind direction can influence the flow of air on an airplane airfoil (Figure 5.30 *Left*). The user can experiment with scenarios by blowing on the paper to change the wind direction to visualize the effects of wind on different designs of airplane wings on display. This application demonstrates that an existing media, such as an exercise sheet, can become interactive to aid in the learning of complex subjects.

Digital Paper Prototyping

Paper prototyping is a common practice in product and interaction design because it allows for quick interaction cycles. This application demonstrates the combination of physical paper prototyping with digital functionality. Gesture controls might be experimentally designed by connecting paper sketches with the functionality, as shown in Figure 5.30 *Right*. After sketching a circular dial, the designer quickly experiments with different gestures such as tapping and swiping to change the volume on the digital prototype.

5.9 Limitations and Future Work

In this section, we discuss some of our system's current limitations, which represent our targets for future work.

5.9.1 Electronics

Each piezoelectric sensor in our system connects to an amplification circuit that we designed for our research purposes. In its current form, the amplification circuit is relatively large and needs an external power supply, limiting the portability of our system. However, we plan to miniaturize the electronics further and re-designed them as small independent portable modules. We aim to reach a point where each piezoelectric sensor is packaged as a small device with the amplification circuit and powered by a battery. We envision that such a modularized system may lead to the design of sensing paper clips that can be easily attached or de-attached to enable interactivity on paper.

5.9.2 Persistent vs. Momentary Touch Sensing

As described throughout the paper, our system currently excels in sensing interactions that actively produce vibrations, such as swiping. However, we are still facing challenges in sensing persistent touching interactions, as vibrations caused by touching the paper fade with time. As a result, it is currently challenging to enable interactions that depend on persistent touches. In future work, we plan to address this issue by further improving our system to detect when fingers move away from the paper after contact by analyzing the features of vibrations generated in each scenario.

5.9.3 Multi-touch Detection

Our system, in its current state, admittedly lacks the ability to detect multi-touch interaction, since we are using passive vibroacoustic sensing. We are currently investigating other ways to enable multi-touch interaction-based exclusively on vibroacoustic sensing. For example, we may resort to extracting more features in the vibrations, such as detecting multiple peaks in each signal's power spectrum.

5.10 Discussion and Conclusion

In this chapter, we presented PaperAware, a novel system that makes standard paper interactive as is by using vibroacoustic sensing. By leveraging the vibrations on the paper's surface as a means for sensing interaction, we turn standard paper into an interactive surface when attached on top of four thin piezoelectric sensors. Our ad-hoc approach is non-intrusive to the material, reversible, and is compatible with existing paper. We also developed a localization technique, ARSS, to process these signals and localize the contact point on paper. Our technique adapts to the environment, neutralizes non-idealities in the system, and background noise and minimizes the influence of vibration propagation loss and other variables.

Researchers have demonstrated compelling examples of paper interactivity using various methods, including instrumented environments and paper. Our system offers several unique advantages over prior work, including; eliminating the need for pre-fabrication or permanent instrumentation of paper. The thin-film piezoelectric sensors occupy a marginal area of the paper to provide users with ample space for interaction. Our system supports a wide range of rich interactions and contact-less interactions, such as blowing on the paper's surface, and our adaptive localization technique.

Meanwhile, our system currently excels in sensing interactions that actively produce vibrations, such as swiping. However, we are still facing challenges in sensing persistent touching interactions, as vibrations caused by touching the paper fade with time. Also, since we use passive vibroacoustic sensing, our system admittedly lacks the ability to detect multi-touch interaction. We plan to address these limitations in future iterations of our systems.

We also presented in this paper a design space for paper interactions that highlight the currently supported capabilities and outlines a vision for a rich vocabulary of paper interactions that extends the role of paper of a passive medium to become an interactive surface.

By enabling surfaces to be sensed acoustically using the natural properties of materials, they can transform into responsive and dynamic materials that take us a step closer to develop technologies with natural sensing capability.

Chapter 6

The Axis of Disappearance

"*Electronic objects are disembodied machines with extended invisible skins everywhere.*"

— Anthony Dunne and Fiona Raby

6.1 Introduction

This chapter extends PaperAware as a project by presenting a series of experiments that further integrate a transducer into sheet material with the ultimate goal of developing a material that can sense through mechanical vibration. It presents the steps taken for fabrication and learnings from the process.

6.2 A Sliding Scale of Integration

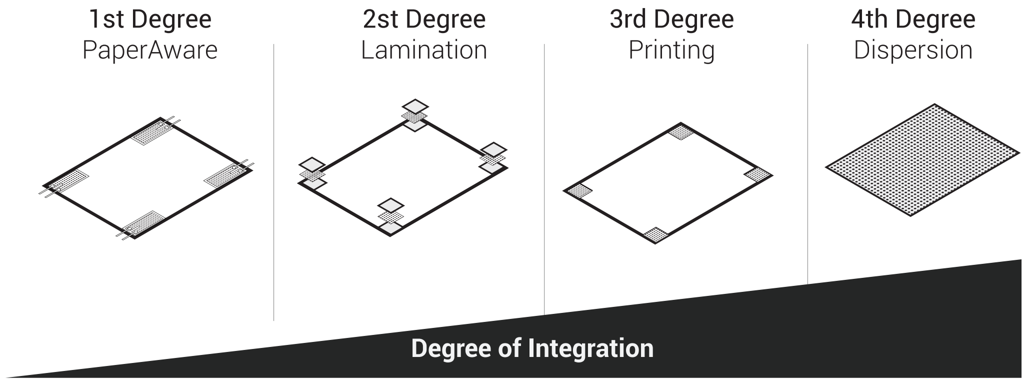


Figure 6.1: Diagram of the Axis Of Disappearance with different degrees of integration between piezoelectric transducer and paper as the base material.

As previously mentioned, leveraging material property response may present new opportunities for developing technologies that can blend into the material palette of the world. While PaperAware demonstrates the potential for interactions with paper as a vibroacoustic material. It still implements the sensor as a separate element from the material itself. Based on the framework proposed in Section 3.4, Figure 6.2 presents the implementation of PaperAware as a bottom-up approach to sense interaction.

As a further development from PaperAware, the question this thesis seeks to explore is how deeply a material can integrate a transducer. To address this question, further exploration into methods to fabricate paper as vibroacoustic material is worthwhile.

The methods of fabrication are in a sliding scale of integration, *The Axis of Disappearance* (Figure 6.1). This axis is a road map for a series of experiments that seeks to increase the coupling between transducer and base material with the final objective to create a paper with inherent vibroacous-

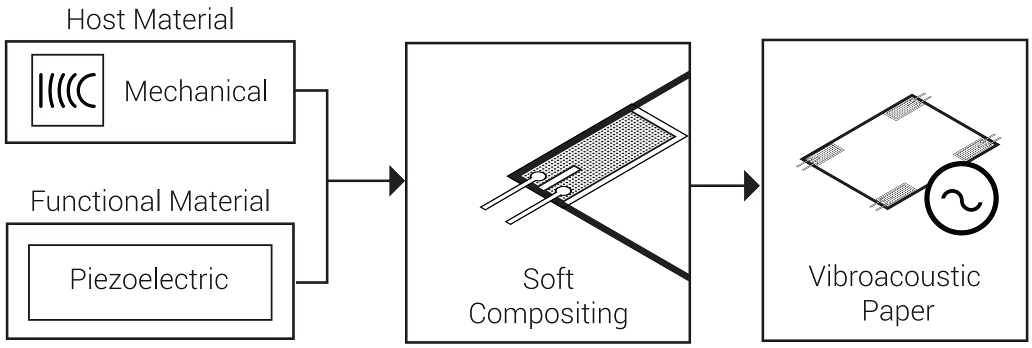


Figure 6.2: Diagram illustrating the use of mechanical vibration as the inherent property leveraged for sensing in PaperAware.

tic sensing capability.

6.2.1 1st Degree: PaperAware

PaperAware demonstrates a temporary integration between paper and transducer through the use of commercially available sensors attached and deattached from paper. Figure (6.3). A benefit of this ad-hoc approach to sensing is that a range of materials can transform into active sensors by leveraging its property response to vibration.

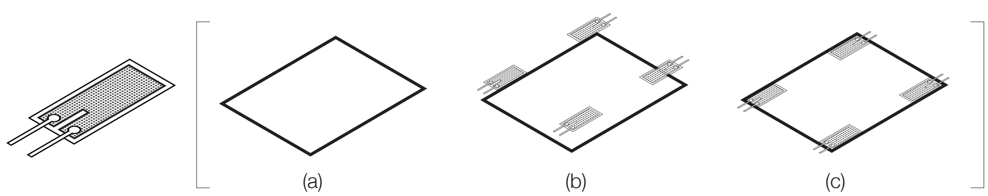


Figure 6.3: Diagram demonstrates the soft compositing strategy as the first degree of integration. *(a)* Standard paper *(b)* Four piezoelectric sensors positioned on corner of paper *(c)* Sensors are temporarily attached to paper surface.

As demonstrated in Chapter 4.3.4, any standard paper can become an interactive interface without requiring pre-fabrication steps. Additionally, this strategy reduces the waste of sensors since it can be re-utilized for new sheets of paper.

The disadvantage of this approach is that sensors must be manually clipped on to the paper as a target material at specific positions. Additionally, it is important to match the sensor and paper's compliance to optimize the transfer of energy. Although it leverages the material response and represents a bottom-up approach to sensing, the sensors can have a tighter physical coupling with the material than demonstrated by PaperAware.

6.2.2 2nd Degree Lamination

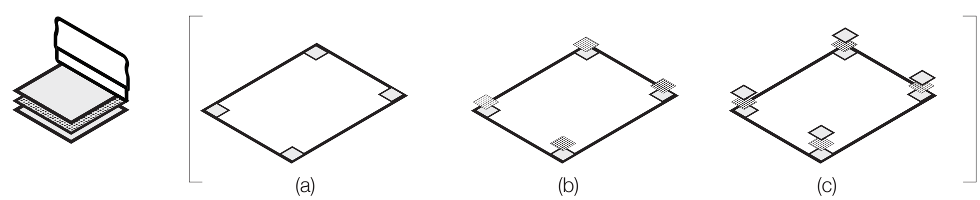


Figure 6.4: Diagram illustrats lamnination technique as a second degree of integration. *(a)* Lamination of bottom electrodes *(b)* Lamination of piezoelectric thin film *(c)* Lamination of top electrodes on paper.

The second degree of integration involves embedding piezoelectric thin film in paper through a lamination process as shown in Figure 6.4. This integration combines printed electronic traces and laminated with a piezoelectric thin film.

This approach comes with a trade-off, while an ad-hoc approach to sensing, as shown in PaperAware is non-intrusive to the material, the permanent integration of the transducer extends the capability of the material itself. This degree of integration results in a material interface with inherent sensing capability.

The limitation of the vibroacoustic paper laminate is that the fabrication method still requires integrating two-hybrid materials with different mechanical and aesthetical properties. Another downside is that the lamination process changes the appearance and compliance of the target paper material. The regions laminated with piezoelectric thin film will have different thickness and material quality than the rest of the paper.

6.2.3 3rd Degree: Piezoelectric Printing

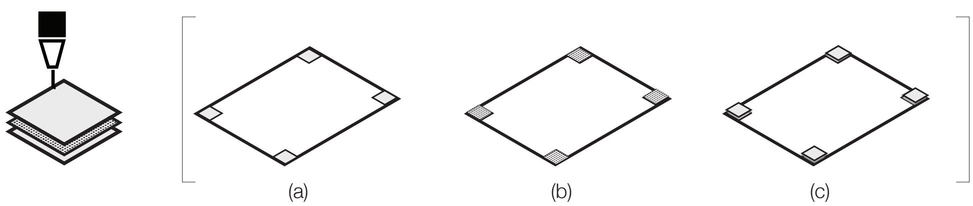


Figure 6.5: Diagram the steps to print vibroacoustic sensors on paper *(a)* Deposition of bottom electrodes *(b)* Deposition of piezoelectric resin or ink *(c)* Deposition of top electrodes.

The 3rd degree of integration consists of directly printing vibroacoustic sensors on sheet material through a multi-layer and multi-material process.

Printing is a compatible technique with the medium of paper and sheet material. Once printed, the piezoelectric material and electrodes will become an inherent part of the paper surface. The result will retain the *paperness* in terms of look and feel. Meanwhile it will enable the paper to express an electrical signal when manipulated.

Another benefit of printing is that it provides design freedom to experiment with different sensor footprints, positions, and architectures in the paper. Additionally, it can augment printed graphics and designs.

Since the medium will absorb the printed layers, the sensor will be compliant. Hence the transfer of mechanical energy to the printed transducer will be highly efficient. From an interaction point of view, we can envision creating interactive posters, wallpapers, or coatings that once applied to sheet material it will enable that material to sense. In this respect, vibroacoustic sensor printing presents an optimal integration with advantages over temporary augmentation and lamination.

6.2.4 4th Degree: Dispersion

Coelho et al. (2009) demonstrates the insertion of electronic elements into paper during the pulp making process. The same process can enhance paper with vibroacoustic sensing by imbuing in pulp piezoelectric particles during the paper making process.

Sappati and Bhadra (2018) review different methods to fabricate vibroacoustic material through the dispersion of piezoelectric particles in polymers and paper as a substrate.

These techniques can create a paper sheet that can inherently express charge on mechanical displacement across the whole surface, given the homogeneous integration between the piezoelectric particles and the paper fibers. The only necessary condition is to attach conductive electrodes to the paper's surface to collect the charge from the material.

Although this technique demonstrates a seamless integration of both transducer and base material, it has a significant drawback. As demonstrated in Section 4.2.4, techniques for acoustic sensing are already efficient by strategically positioning point sensors on a surface, without the requirement of a whole the surface to exhibit piezoelectric response.

Using point transducers may be more efficient, they can occupy a small footprint of the surface and be useful for inherent material sensing. Hence, creating a special paper in which the surface has piezoelectric material can impractical for three main reasons: first, it requires the fabrication of a particular type of paper, rather than augmenting existing paper media (which can be achieved by printing or lamination) this limits the scalability of this approach. Secondly, it can makes more use of material than what is required for sensing, leading to material waste. Thirdly, piezoelectric materials are relatively expensive compared to materials used in paper making. Hence, the amount of source material required to cover a whole area of the paper will drastically increase the per unit cost of paper.

6.3 Fabrication Experiments

This section presents a series of fabrication experiments that navigate the *Axis of Disappearance* and report on accomplishments, failures, and learnings in attempting to create paper and sheet material with inherent vibroacoustic sensing capability.

6.3.1 Fabricating Laminates (2nd Degree)

Fabrication Technique

The fabrication of piezoelectric paper laminates involves using piezoelectric thin film permanently laminated on one side of the paper. One of the advantages of utilizing piezoelectric thin film over piezoelectric ceramic disks is that a PVDF thin film has a closer acoustic impedance to organic material, which maximizes the transducer response as a function of paper vibration (see PiezoTechnicalManual, 2020, p. 2).

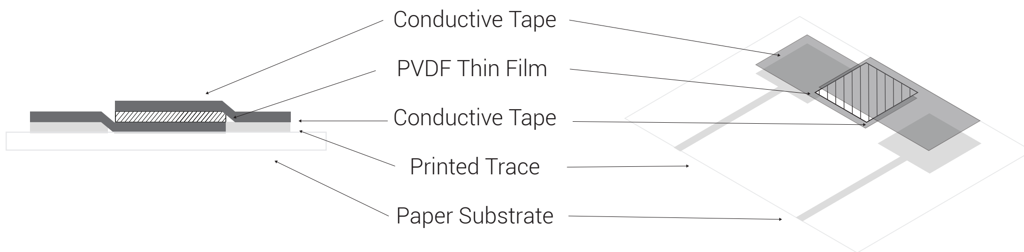


Figure 6.6: Diagram showing cross section and isometric view of lamination technique to embed PVDF thin film into paper.

Embedding the PVDF thin film in a conformable surface is a challenge given the multilayer structure necessary to make the thin film into a transducer (as mentioned in Section 4.3.4). Piezoelectric polymers such as PVDF or copolymer (PVDF-TrFe) can be sourced as a raw thin film (without electrodes) or already embedded with surface electrodes suppliers from suppliers such as TE Connectivity.

A vibroacoustic laminate consists of a 28 μm piezoelectric thin-film, with pre-applied top and bottom electrodes, laminated onto standard paper. The thin film can be acquired in sheets of multiple sizes.

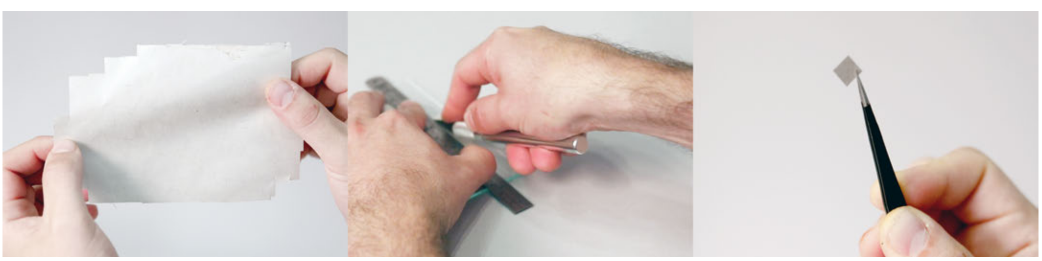
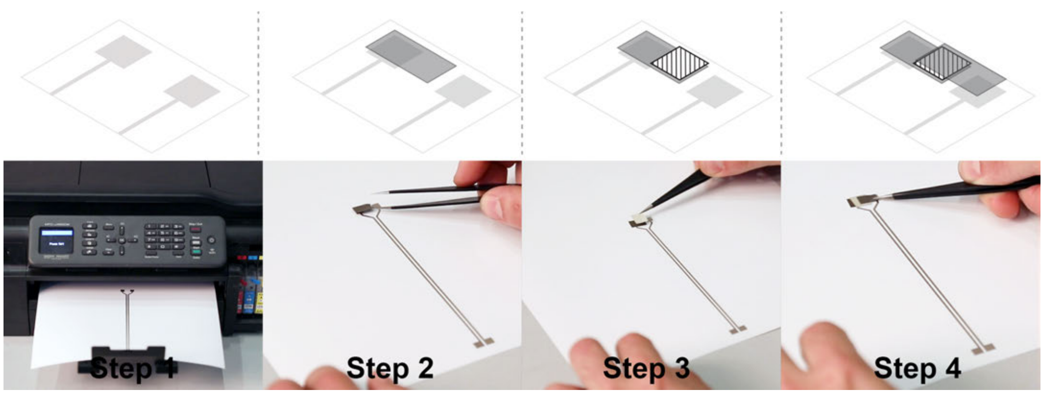


Figure 6.7: Steps for cutting the piezoelectric thin film into dices that can be laminated on paper surface.

Over a glass surface, using a sharp blade, the thin film is diced into 1cm by 1cm squares as shown in Figure 6.7. A challenge while cutting PVDF thin film is that the force applied by the blade can cause particles from the electrodes to come in contact, causing the thin film to *short*. A 5V charge can be applied to the top and bottom electrodes of the film to eliminate residual particulates of the conductive layers.

The piezoelectric film is connected to a conditioning circuit by traces printed using a commercially available Brother DCP-J140W inkjet printer and Mitsubishi NBSIJ-FD02 Silver Nanoparticle Ink on an NB3GR Resin Coated Paper. The traces have a 1mm width and a 10cm x 10cm length that take the signal from the film to a connection point on the edge of the paper.

Printed electrodes provide the design freedom to position the sensors at different points on the paper surface. To adhere the thin film with the paper surface 50 μm double-sided conductive adhesive is applied on the top and bottom thin film to collect charge. (Figure 6.6).



Demos

The following demos demonstrate application ideas for vibroacoustic paper laminates. The purpose of these demos is to further the design space proposed by PaperAware and explore vibroacoustic laminates as the next step of integration between the transducer and base material.

The first demo consists of a printed interactive drumkit (Figure 6.8). In this demo, a vector graphic of a drum kit printed on paper is augmented with piezoelectric materials laminated on the underside of the paper.

The vibroacoustic paper connects to a conditioning circuit and an audio interface. In OpenFrameworks, a peak detector recognizes taps on the drum pieces and trigger sounds that play on speakers. The amplitude changes the timbre and pitch of the sound based on tap intensity. A computer display provides visual feedback.

Figure 6.8: Image of laminated vibroacoustic paper demos. *Left:* Drumkit demo using two vibroacoustic sensors laminated on the underside of paper to detect touch interaction with printed graphics. *Right:* Interactive dandelion demo using wind vibration to enhance interaction with paper with graphics on screen.

The second demo utilizes vibroacoustic paper as a wind sensor. This demonstration implements an interactive pop-up book with visuals on a computer display that augments the paper interaction. Once the paper dandelion is blown seeds propagate from the center of the screen responsive to the intensity of vibration sensed by the paper.

In the third demo the vibroacoustic paper senses interaction with writing and cutting instruments. The paper's electrical signal is processed by a feature extractor that uses frequency components to train a support-vector-machine (SVM), model. The SVM can discriminate between two classes of writing implements (a pen or a sharpie) and two classes of cutting implements (blade and scissors) as shown in Figure 6.9.

Figure 6.9: Image of laminated vibroacoustic paper demo. *Left:* SVM model classifies interaction between paper and writing implement. *Right:* SVM model classifies cutting implement.

6.3.2 Piezoelectric Printing (3rd Degree)

This experiment explores a technique for screen-printing vibroacoustic sensors. The ability to print vibroacoustic sensors utilizing ink directly on paper is advantageous given its low profile, tight coupling between ink and substrate, and design freedom. It realizes the objective of creating a material with inherent vibroacoustic sensing capability.

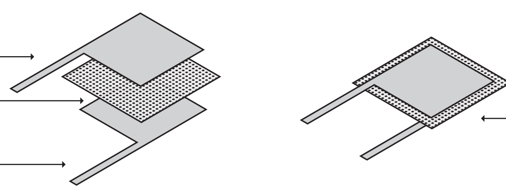


Figure 6.10: Diagram of layer structure for vibroacoustic sensor printing. *Left:* Exploded diagram of the printed sensor. Bottom Ag electrode, middle layer Piezo FC ink, and top PEDOT:PSS layer. *Right:* Diagram of the final sensor with three layers applied.

Additionally, it opens new possibilities for design, prototyping, and exploring a combination of vibroacoustic sensors with graphic design. The challenge of printing piezoelectrics is to work with piezoelectric materials in ink or resin form.

This experiment uses Arkema P(VDF-TrFE) piezoelectric ink printed on different substrates along with top and bottom electrodes using screen printing techniques. Figure 6.10 shows the basic architecture of a sensor. The deposition is followed by the poling process to increase the piezoelectric response of the transducer.

Three masks are used for the deposition, two horizontally mirrored masks for the top and bottom electrodes with identical dimensions as shown in Figure 6.11 *Left* and *Right*. And a third mask for the piezoelectric ink that has a larger area than the electrodes as shown in Figure 6.11 *Center* so the piezoelectric can act as an insulator to prevent the top and bottom electrodes from coming into contact.

Figure 6.11: Mask designs for vibroacoutic sensor. *Left:* Bottom electrode. *Middle:* Piezoelectric layer. *Right:* Top electrode.

Surfaces with low roughness are better suited for a homogeneous deposition of the bottom electrode on a substrate. The uneven deposition of a bottom electrode will result in a dielectric breakdown of the material during the poling step which causes the fabrication to fail. In this exploration, the substrates used are DuPont Kapton thin film, Powercoat HD Electronics paper, and Standard Paper. The scan electron microscope (SEM) image in Figure 6.12 shows that the Standard paper exhibits a much higher surface roughness in comparison to Kapton and Powercoat HD paper.

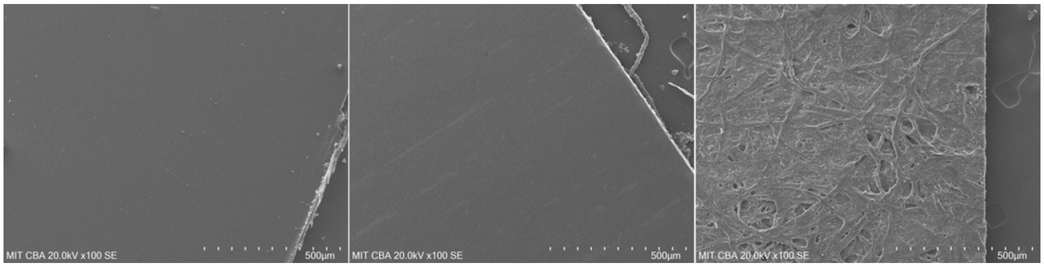


Figure 6.12: Scan electron microscopy of substrates for estimation of surface roughness. *Left:* Kapton. *Middle:* Powercoat HD Electronics Paper *Right:* Standard Paper

In this step, the layers are screen printed manually using a 100 μm Kapton sheet as a mask on the substrate attached to a hot plate. The bottom electrode uses Silver NanoParticle ink deposited directly on the substrate. Then the Arkema P(VDF-TrFE) ink and a lastly a PEDOT:PSS Clevios SV 4 ink applied as a top electrode. Each layer requires 20 minutes drying time at 110°C on the hot plate Figure 6.13.

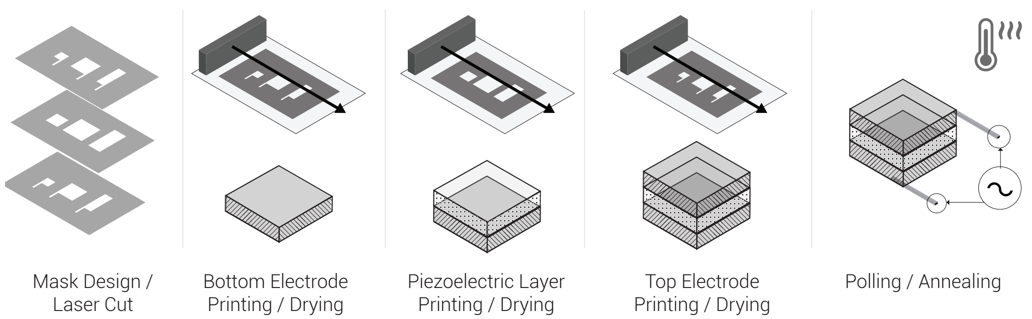


Figure 6.13: Summary of steps taken to experiment in printing piezoelectric ink and electrodes on a flat substrate.

Following the drying of the three layers, terminations are added to the sensor using conductive epoxy and connected to a power transformer. In the poling step a 1Hz AC sinusoidal signal is applied with progressively increasing in amplitude until it reaches the minimum coercive field strength of

PVDF.

The minimum coercive field strength for PVDF is around 50 kV/mm. Peak performance is 100kV/mm. Hence, to successfully poll a 100 μm thickness PVDF thin film, it requires a minimum of 5kV of voltage.

During the polling process, the samples experienced a breakdown at 0.5kV of power. When the break down occurs at a lower voltage than the minimum coercive field of the material, it indicates that there is a dielectric breakdown of the sample caused by the uneven application of layers. Initial experiments demonstrated limited success. Although the first printed samples exhibited a low piezoelectric response, the process proven to be possible by tuning the processes and parameters for deposition and poling.

Unfortunately, the experimentation in piezoelectric printing was halted due to closure of MIT Campus as a response to the COVID19 pandemic.

6.4 Reflection on Printing Experiment

The success of a printing process for piezoelectric ink requires the uniform deposition of all layers of the transducer. It also requires each thickness to be precisely controlled and known to calculate the ideal polling voltage.

For an even deposition, the speed, pressure, and angle of the screen printing blade must be computationally controlled. In addition to these requirements, the selection of inks for the bottom and top electrodes and screen printing mesh also plays an essential role in successfully depositing the ink on the substrate surface in a uniform manner.

While production scale machines can achieve this level of parametrization and control; printing efficient piezoelectric transducers is still challenging for manual or DIY processes.

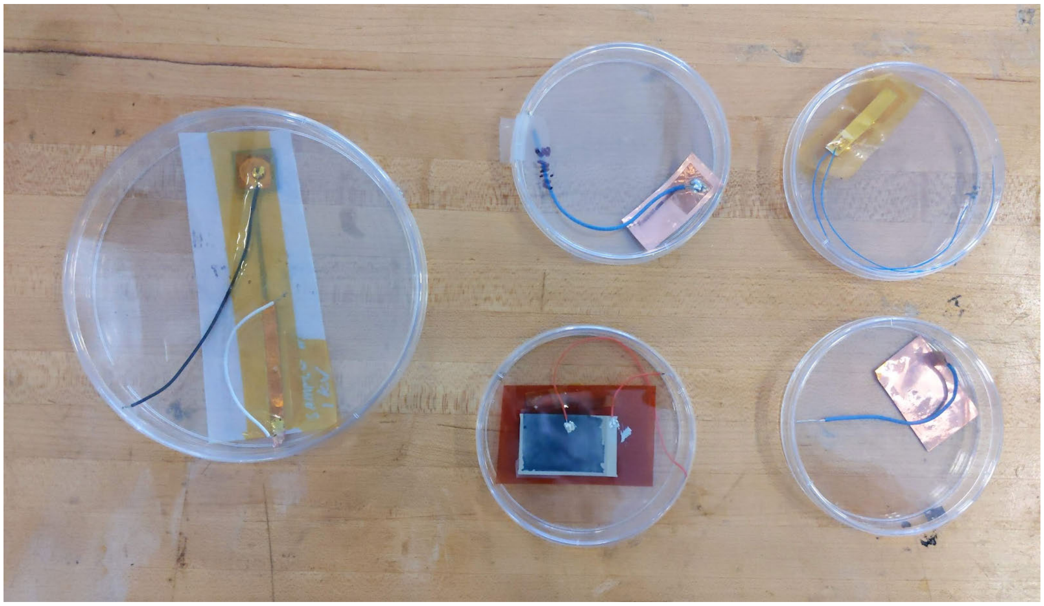


Figure 6.14: Collection of piezoelectric screen printing fabrication experiments.

The challenges faced may explain why there are not many examples of DIY or manual vibroacoustic printing techniques reported in the literature compared to conductive ink, as demonstrated by Kawahara et al. (2013).

The polling process is non-trivial and relies on the precise deposition of the ink layers. Additionally, the poling variables, including voltage, AC signal, periodicity and temperature, have been tuned based on layer thicknesses and material selection.

Although the experiment in printing piezoelectric transducers did not result in a fully functional sample, it shows promise when it comes to interaction since it can satisfy the condition of creating materials with inherent vibroacoustic sensing capability.

The experimentation documented in this thesis can hopefully inspire researchers to continue the manual fabrication of such unique materials.

Chapter 7

Vibroacoustic Materials & Beyond

7.1 Introduction

This chapter presents a future vision for a bottom-up approach to sensing that utilizes vibroacoustic materials in concept applications and future scenarios.

7.2 Vision & Future Work

7.2.1 Vibroacoustic Sensing Skin

While this thesis focused on paper as a vibroacoustic material that can sense touch and airborne vibrations, vibroacoustic materials can go beyond the domain of HCI to become a *smart* skin with the ability to sense interaction with environmental elements at an architectural and city scale.

For example, as a concept, a boat's sail can be augmented by a vibroacoustic sensing skin that enables the surface of the sail to sense the distribution of wind with a high degree of precision (Figure 7.1). The data can optimize

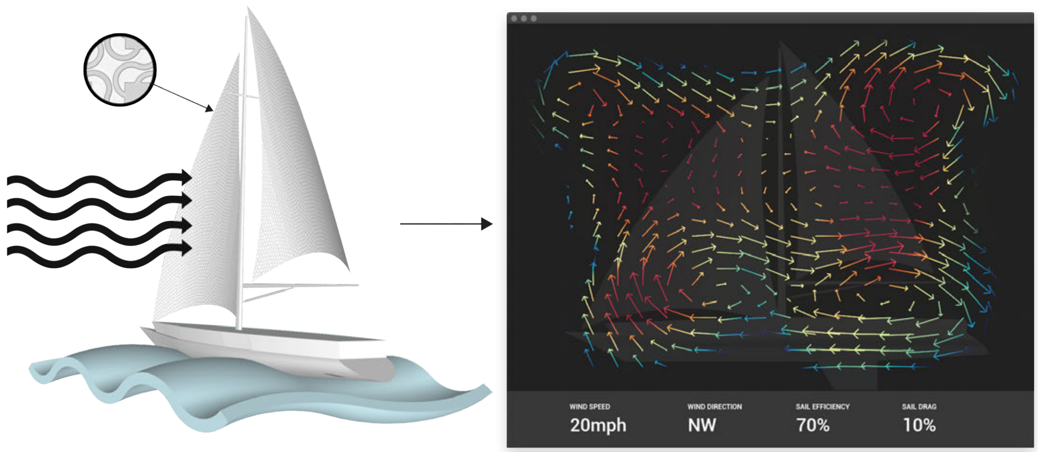


Figure 7.1: Concept image of large scale vibroacoustic sensing skin applied on boat sail.

future sail designs and predict the tear and wear of the sail mesh over time. Similarly, by augmenting the fin a boat with vibration sensing capability, it can capture and respond to changes in water streams to optimize navigability and course correction.

In aerospace engineering, vibroacoustic sensing skin can *wrap* space structures localize the impact of microparticles with the surface of spaceship such as the International Space Station (ISS). This data can inform the dispatch of repair crews to damaged locations and prevent future impacts (Figure 7.1.b).

Flexible architectural structures such as tents and building facades can also be augmented with vibroacoustic sensing to diagnose damage caused by rain spells' increasing safety and longevity. At a city scale, vibroacoustic sensing capability can become a construction material used in buildings, roads, bridges, and electrical power systems. Structures built with vibroacoustic materials can predict and prevent fault, fatigue, and potential collapse.

7.2.2 Integrated Vibroacoustic Material Printing

Mahadeva et al. (2016) demonstrate the fabrication of piezoelectric paper material with a high piezoelectric response. Cui et al. (2019) implements a method for 3D printing of piezoelectric materials with a selective directional response. Despite current research, there are no current reports of an integrated system that incorporates design, printing, and poling of materials as a single process.

The challenge to print vibroacoustic materials is that it requires precision to deposit materials with low roughness and uniform layers thickness, as shown in Figure 7.2. Furthermore, as described in Section 4.3.4, the printing step has to be followed by polling to increase the electrical response of the material.

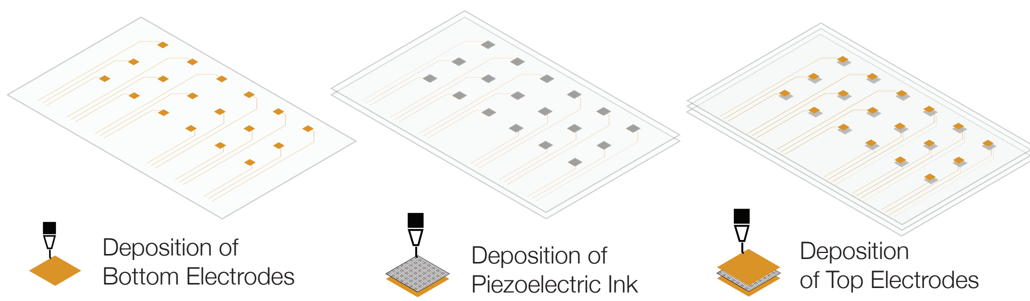


Figure 7.2: Diagram for multi-layer and multi-material printing process to produce a printed microphone array.

An integrated printing system incorporates all these steps into a single process. It consists of a precise multi-material deposition head for the electrodes and piezoelectric layers. Meanwhile, the printed sample is subjected to an electric field and heated to a given temperature, as illustrated in diagram 7.3. The process can incorporate settings, including feature size, layer thickness, drying time, bed temperature, polling voltage.

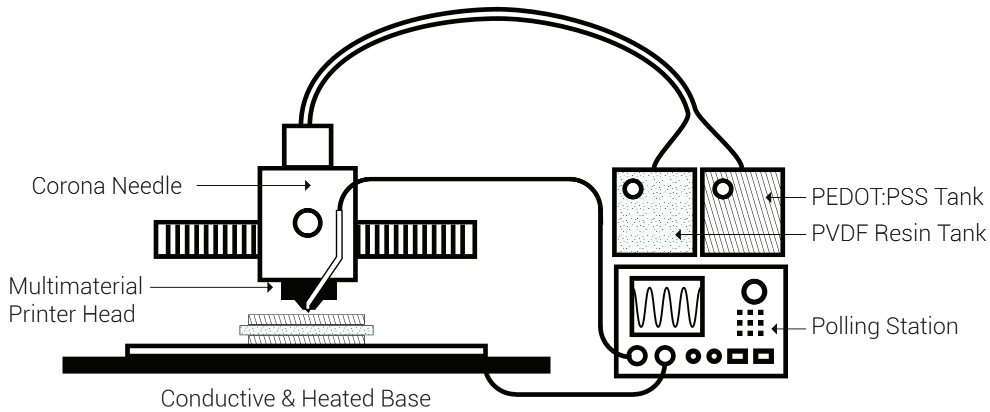


Figure 7.3: Block diagram for designing an integrated vibroacoustic material printing machine.

Vibroacoustic materials printed on demand can apply to audio engineering for large-scale noise-canceling sheets and acoustic holography surfaces. In the HCI domain, it can be used to prototype and experiment novel sensing techniques with the freedom to experiment with different sensor geometries and designs. For the creative industry, it can augment printed media and graphic design with interactive capability.

7.2.3 Above and Below the Acoustic Range

Bidirectionality and wide frequency range are unique characteristics of piezoelectric materials, as described in Section 4.3.3. While the implementation in this thesis focuses on the acoustic spectrum, increasing the frequency of operation to above 20Khz and utilizing emitter/receiver architectures for a vibroacoustic material can increase the latitude of application domains.

Combining the ultrasonic range with printed vibroacoustic surfaces may enable the large scale manufacturing of paper-thin ultrasonic devices for non-intrusive imaging and diagnostics (Figure 7.4 Right).

Figure 7.4: Concept images of future vibroacoustic materials. *Left:* microphone array printed on paper sheet. *Right:* Ultrasonic sheet material being used as an imaging device.

For example, printed transducers arranged in an emitter/receiver architecture cover factory walls and floor to sense and compensate for micro-vibrations that cause imprecise production of nanoscale devices such as microchips. Meanwhile, it can non-intrusively image materials and machinery for faults in production lines.

Chapter 8

Conclusion

This thesis demonstrated that it is possible to follow a bottom-up approach to leverage material vibration to sense interactions. The thesis also introduced a theoretical framework to leverage material properties for sensing. PaperAware is an example of leveraging vibration, a mechanical property of materials, to sense interactions on paper.

The possibility of sensing through material properties can contribute to the long term vision of ubiquitous computing and the paradigms that trail its path since it fosters the emergence of materials that are naturally sensing.

While most techniques in HCI attempt to enhance materials with interactivity through a top-down approach, by embedding active sensing layers in inert materials. A bottom-up approach holds the potential for the development of materials with inherent sensing capability. However, this approach has currently been underexplored in the context of HCI.

Wiberg (2017) suggested that the material-turn in HCI can reintroduce computing to the world of materials, turning the attention to the qualities and properties of a material in the practice of design.

This thesis implemented this perspective by demonstrating viable ways in which technology can blend with the environment by exploring the functional properties of materials.

Materiality can play a central role in the interaction loop by elevating the condition of materials from passive or structural elements to become sensing enablers.

A bottom-up approach to sensing contributes to the broader view of human-material-interactions (HMI), in which materials can sense and respond to the user directly. A perspective that can enable novel interaction paradigms and new aesthetics for computing technology to emerge. Ultimately taking steps closer to Mark Weiser's vision in which "technology blends with everyday life until it is indistinguishable it" (Weiser, 1991).

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