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Sanad Bushnaq, Joao Wilbert, Ken Nakagaki, Saman Farhangdoust, Hiroshi Ishii, "VibroAware: vibroacoustic sensing for interaction with paper on a surface," Proc. SPIE 12049, NDE 4.0, Predictive Maintenance, and Communication and Energy Systems in a Globally Networked World, 1204909 (18 April 2022); doi: 10.1117/12.2617330

Event: SPIE Smart Structures + Nondestructive Evaluation, 2022, Long Beach, California, United States

VibroAware: Vibroacoustic Sensing for Interaction with Paper on a Surface

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ABSTRACT

Vibroacoustic sensing is a method to investigate and enable tangible interaction on surfaces. One of the main challenges in this field is to make a sheet of paper on a surface interactive without either prefabrication or permanent instrumentation. This research presents VibroAware, a novel system that makes paper on a surface interactive as is by leveraging vibrations. The sheet of paper becomes interactive when users attach it to four thin piezoelectric transducers. Users interact with the sheet of paper on the surface by touching or blowing, which produces vibrations captured by our system. In this research, an algorithm is developed to enable localization and adapt to environmental noise without requiring analyzing material properties. VibroAware offers users the ability to test and prototype faster, and create interfaces using vibroacoustic sensing on a sheet of paper more intuitively. This research presents a future vision for using vibroacoustic sensing to enable interaction on a sheet of paper that opens opportunities to utilize inherent material properties, such as vibration.

Keywords: Vibroacoustic, vibration, sensing tangible, localization, interaction

1. INTRODUCTION

Vibroacoustic sensing is investigated in the Human Computer Interaction (HCI) community to enable tangible interaction with physical objects. Vibration is an inherent material property that carries valuable information about the interaction. Vibroacoustic sensing extracts such information from vibrations caused by direct or indirect contact. This sensing approach is non-intrusive, occlusion-free, and does not require devices attached to users, and it can be used to enable tangible interaction through localization and classification of an impact point on rigid objects and surfaces, as mentioned in Ref. 1.

Ref. 2–4 successfully use vibroacoustic sensing to detect tangible interaction on objects. Ref. 5 uses eight electret pickups attached to a ping pong table to localize the ball's position whenever it hits the table's surface using time difference of arrival algorithms. Ref. 6 employs vibroacoustic sensing to localize taps on large glass surfaces. Researchers in Ref. 7 use vibroacoustic sensing to extend the interactive area of mobile phones and tablets. Meanwhile, Ref. 8 uses vibroacoustic sensing to localize continuous touch by attaching active transducers to the user's fingers, and Ref. 9 utilizes microphones in mobile devices to localize touch on rigid surfaces. Ref. 10 also applies time difference of arrival algorithms on slip pulse waves to localize and track tap and swipe interactions on solid surfaces. Ref. 3, 11, 12 also use vibroacoustic sensing to classify interactions. Finally, Ref. 13,14 rely on pre-training (data template matching) to localize touch using passive vibroacoustic sensors attached to a rigid surface.

However, we noticed that using vibroacoustic sensing to transform an ordinary sheet of paper into an interactive surface is still an open research space, as we explain below and show in Figure 1. Paper is a rich medium that inspires creation and innovation. It is low-cost, recyclable, and is commonly used every day in various forms. Paper also allows vibrations to propagate, which enables vibroacoustic systems to utilize this inherent material property to develop various applications. For example, Ref. 15 leveraged vibration on paper to create an origami speaker.

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NDE 4.0, Predictive Maintenance, and Communication and Energy Systems in a Globally Networked World, edited by Norbert G. Meyendorf, Saman Farhangdoust, Christopher Niezrecki, Proc. of SPIE Vol. 12049, 1204909 · © 2022 SPIE · 0277-786X · doi: 10.1117/12.2617330

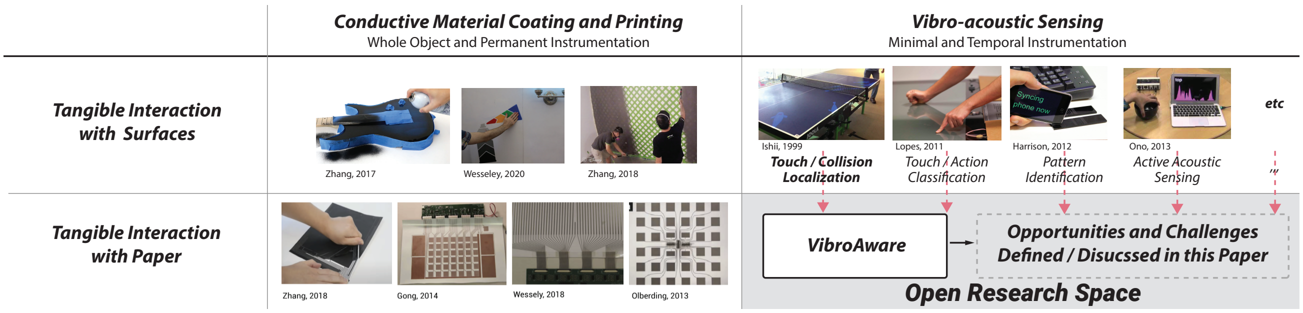


Figure 1. Prior work has successful examples in augmenting surfaces using permanent instrumentation techniques and vibroacoustic sensing. Nevertheless, augmenting paper is mostly limited to permanent instrumentation techniques. This makes detecting interaction with a sheet of paper on a surface using vibroacoustic sensing an open research space.

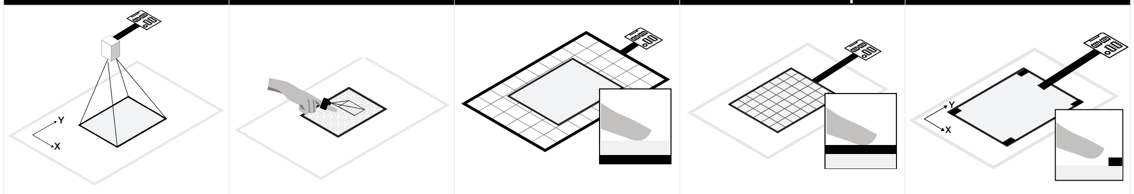
Figure 2 summarizes the most common techniques used to make a sheet of paper on a surface interactive: Overhead cameras, on-finger cameras, instrumented surfaces, permanent instrumentation of the sheet, and our proposed vibroacoustic sensing.

Overhead cameras are a common approach to enable paper-based interaction using an external device in the surrounding environment. In this approach, researchers detect interaction on a sheet of paper on a surface using a stationary camera that is usually above the sheet. The camera detects touch or other forms of tangible interaction on sheet materials using computer vision, as explained in Ref. 16–23. The second approach is using wearable cameras to add mobility to the system. But this requires the use of special paper with printed markers, such as Ref. 24–29. When using cameras, the processing load usually depends on the resolution and frame rate, so the load is often heavier compared to other approaches. The third approach is to fabricate rigid conductive surfaces underneath the sheet to make it interactive, as shown in Ref. 30–32. This approach is occlusion-free, and can be mobile when the processing circuit is miniaturized, but requires the additional surface. The fourth approach is permanent instrumentation, which follows the vision of Ubiquitous Computing in Ref. 33 and Computational Materials in Ref. 34. This approach integrates the sensing capability into the paper's material itself by instrumenting the sheet permanently using conductive coating, pre-fabrication or by imbuing sensors directly on the sheet's surface. For example, Ref. 35 prints conductive traces on paper to detect touch, and Ref. 36–38 detect cuts and various tangible interactions. Permanent instrumentation can also be an effective technique for general surfaces, as demonstrated in Ref. 39, 40 and shown in Figure 1. However, permanent instrumentation usually involves pre-fabrication steps, such as overlaying the sheet with dense arrays of conductive materials, which is irreversible, intrusive to the material and cannot be transferred to another paper sheet. Figure 3 shows a summary of prior work on paper augmentation.

The above review shows that making a sheet of paper on a surface interactive using an inherent material property of the paper (vibration) through vibroacoustic sensing with minimal instrumentation and without resorting to intrusive techniques is still an open research space, as we explain in Figure 1.

We suspect a reason behind this is related to the complexity of vibroacoustic systems in general. Capturing and analyzing vibrations, performing complex computations, and the reflective and dispersive properties of surfaces make extracting useful information from vibrations a challenge, as mentioned in Ref. 10, 41, 42. Many vibroacoustic systems rely on measuring the propagation speed of vibrations. Interacting with a surface produces different types of vibration waves that travel at various speeds and have attenuation models and characteristics that depend on the surface's material. The impact type affects the direction and speed of vibrations produced. For example, tapping on a surface generates vibrations dominated by surface waves, while swiping generates shear waves that decay faster than surface waves, as explained in Ref. 10. That is why such systems need to include the surface's material and properties in their computations and perform complex calibrations based on signal segmentation for each type of vibration waveform produced and its various characteristics (Ref. 10).

The challenges mentioned are valid even without using a sheet of paper on top of the surface. Putting a sheet of paper on top of the surface, for example to interact with already existing printed media, adds a new level of



	Overhead Camera	On Finger Camera	Instrumented Surface	Permanently Instrumented Paper	Vibroacoustic Sensing
Paper type	Standard, existing media	Special	Standard, existing media	Special	Standard, existing media
Fabrication requirement	None	Printed markers	Conductive Array	Conductive Array	None
Sensing Techique	Computer Vision (blob)	Computer Vision (markers)	Inductive (electromagnetic field)	Resistive, Conductive	Vibroacoustic
Processing Load	Heavier	Heavier	Lighter	Lighter	Lighter
Mobility	Stationary (requires fixture)	Mobile (miniaturized circuit)	Mobile (miniaturized circuit)	Mobile (miniaturized circuit)	Mobile (miniaturized circuit)

Figure 2. An overview of common techniques to make paper on a surface interactive. Vibroacoustic sensing is an open research space.

complexity. During interactions with the sheet placed on the surface, different waves of vibrations on both the sheet and the surface will be produced whenever the sheet contacts the surface (Ref. 10,41,43). These vibrations may have different types, opposing phases and may distort or cancel each other when they arrive at the sensors. In addition, vibration propagation speed will differ between the sheet and the surface based on the material type, elasticity, and thickness (Ref. 10,43). Moreover, sensors attached on the sheet may differ in tightness (how tight sensors are attached to the sheet), which may cause an imbalance in the system that leads to inaccurate results. All these issues increase the complexity of the already challenging system. That is probably why using vibroacoustic sensing to enable tangible interaction with a sheet of paper on a surface is still an open research space.

In this research, we present VibroAware, a novel system that makes standard sheet of paper on a surface interactive as is by using passive vibroacoustic sensing. Our system makes the sheet on a surface interactive without the need to include the sheet's or surface's material or properties in computations. It also does not require differentiating between sheet and surface effects, or performing complex calibrations or signal segmentation. That is because we developed an algorithm based on the difference in the total power of vibration measured at each sensor, rather than relying on the waveforms' propagation speed, which makes our system function correctly even when capturing vibrations from the sheet and the surface underneath. Our new algorithm, Adaptive Received Signal Strength (ARSS), also adapts to environmental noise and common non-idealities in hardware to minimize computation errors without relying on pre-training. VibroAware enables users to make standard sheets of paper, including existing printed media, interactive by simply putting it on a surface and attaching it to four passive thin piezoelectric sensors, one on each corner. The sensors occupy a minimal area of the paper to leave users with a large interaction space. Users can then interact with the sheet by touching or blowing on its surface, producing vibrations that our system uses to sense the interaction. As a result, we achieved real-time tracking of touch, swipe, and contactless interactions, such as blowing on the sheet's surface. This approach is non-intrusive to the material, reversible, and does not require pre-fabrication, making it compatible with printed media and applicable to office-like situations. Moreover, we can classify interactions by type (tapping, swiping, pen, or sharpie) through a neural network we trained, leveraging distinct vibration characteristics for each interaction type.

VibroAware is a proof of concept prototype with some limitations, such as the inability to detect multi-touch or stationary touches that do not generate vibrations. Our work is also limited to flat paper on a surface to explore the design space and conduct the evaluation in a desk context (for writing, touching etc), which is one of the most conventional ways to interact with paper. Exploring interactions in mid-air is outside the scope of this work, but it is a step toward exploring a wide and open research space. We hope this motivates researchers in the

	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
VibroAware	**Touch, swipe, angle, blow**	**Vibroacoustic**	**Yes**	**No**	**No**	**Attached**	**Passive**

Figure 3. A summary of prior work on paper augmentation.

community to develop new ideas to overcome the challenges and limitations and continue building on this work to enrich tangible interaction with vibroacoustic sensing. The minimal instrumentation and temporal attachment in vibroacoustic sensing open the door for many new opportunities to design and prototype interaction with everyday objects, materials, and surfaces around us. This is especially critical in ubiquitous computing research, where sustainability and re-usability are two main challenges, as detailed in Ref. 33

In the following sections of this research, we introduce the general architecture for vibroacoustic, describe our system and algorithm, and show the experimental validation results. We also introduce supported interactions and present example applications. We also discuss the challenges and future work of VibroAware. Our contributions described in this research include:

- Exploring an open research space by using vibroacoustic sensing to enable interaction with a sheet of paper on a surface.
- Supporting real-time tracking of touch, swipe, and contactless interaction, such as blowing on the sheet's surface.
- An algorithm based on the difference in total power of waveforms that does not require prior knowledge of material properties and does not need complex calibration nor signal segmentation. It also adapts to environmental noise and non-idealities in hardware expected to exist in vibroacoustic sensing systems.
- Highlighting opportunities and challenges that may inspire future research to enrich tangible interaction using vibroacoustic sensing.

2. VIBROAWARE METHODOLOGY

2.1 Architecture Overview

Figure 4 shows the general architecture of VibroAware. We attach four thin-film passive vibroacoustic sensors on the paper, one on each corner. When users make contact or contactless impact on the paper, vibrations propagate on the paper's surface from the impact point until they reach the sensors on the corners. Sensors convert these vibrations to electric signals. Each sensor is connected to an amplifier circuit that amplifies its output and sends it to an audio interface. The audio interface receives signals from all sensors, each arriving on a separate channel, and sends them to a computer for processing. We then compute the Fast-Fourier-Transform (FFT) for each channel to its characteristics. We then execute *localization* to find the position of the impact point and track it in real-time using the *ARSS* technique we developed. We also perform *classification* to classify

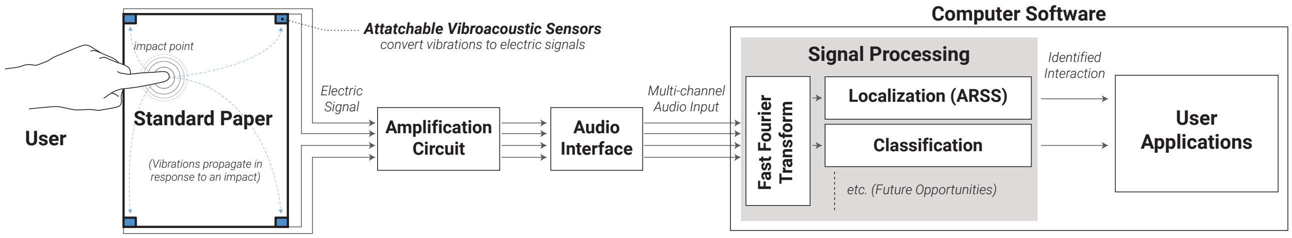


Figure 4. General Architecture of VibroAware. We put the paper on a surface and attach it to four thin-film passive vibroacoustic sensors, one on each corner. Vibrations propagate on the paper's surface from the impact point whenever there is an impact on the paper. Sensors capture these vibrations, convert them to electric signals, and sends them to a circuit with variable amplifier gains. We send the output to a PC for processing. Our algorithm, ARSS, computes FFT for each channel and performs localization to find the position of the impact point in real-time.

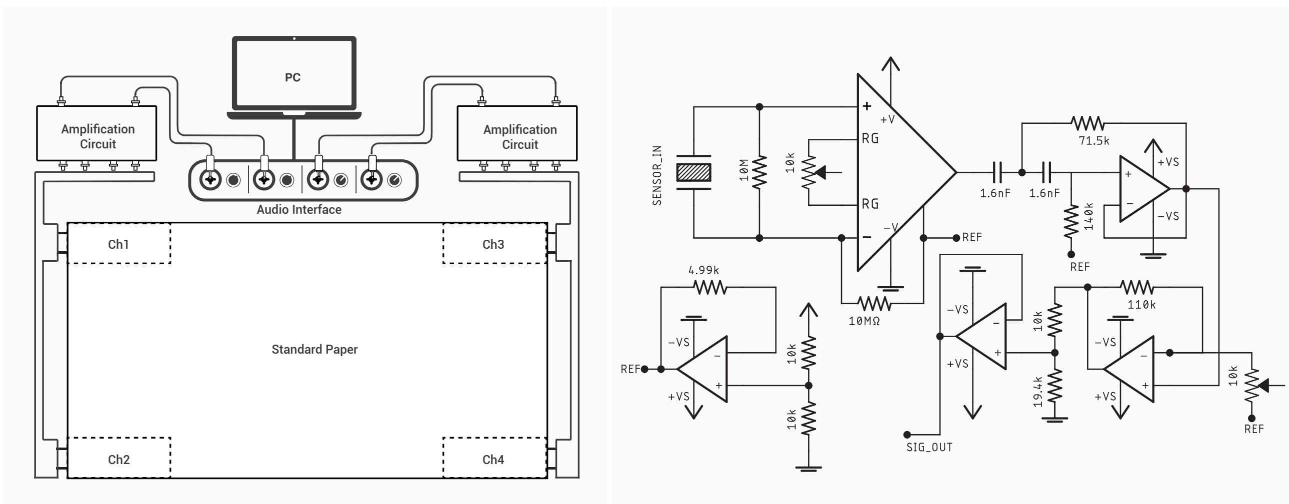


Figure 5. System setup of VibroAware. (Left) Each sensor is connected to an amplification circuit and an audio interface. The audio interface sends all channels to a computer to be sampled, then processed in real-time. (Right) The amplification circuit we designed for VibroAware. Each circuit has a 2-channel, 2-stage amplifier with a high pass filter and an analog output.

the interaction by type. Future opportunities are also open for investigation, such as the one explored on a rigid surface in Ref. 1. We then pass information to the application layer to enable interactivity.

We use four 28μm thin-film piezoelectric sensors (16x41mm) from TE Connectivity (Ref. 44). Sensors are connected to the amplification circuit through custom-designed flexible PCB connectors, as shown in Figure 5(left). These connectors have ground planes on their top and bottom for noise shielding. We designed the amplification circuit from scratch. Each amplification circuit has a 2-channel, 2-stage amplifier with a high pass filter and an analog output, as shown in Figure 5(right). We use an instrumentation amplifier (Analog Devices AD8221 Ref. 45) in the first stage for its performance in noise rejection. The second stage has TLV2374 quad OP-AMP (Ref. 46) that we also use to bias the first stage at 2.5V. The amplification circuit's output goes to a 24-Bit/192 kHz audio interface (Ref. 47) connected to a computer that samples this analog signal at 192 kHz. On the software backend, we built a custom software in C++ to read sampled signals from each channel and process it in real-time. We compute the Fast-Fourier-Transform (FFT) of all channels using Maxim library (Ref. 48). We then compute the localization of the impact point's position and send that information to the application layer, as shown in Figure 4.

2.2 Localization Algorithm

Source localization is the process of estimating an object's position or impact point within a coordinate system (Ref. 49–52). Localization is researched extensively to solve many problems in various fields, including mobile communications (Ref. 53), radar (Ref. 54), and Human-Computer Interaction (Ref. 6). Localization is essential in vibroacoustic-based interaction. We use localization in VibroAware to estimate the impact point's position when users interact with the sheet of paper.

Several localization models exist to address different requirements that cover a wide range of applications. Localization models are typically evaluated based on their accuracy. The accuracy is defined as the average error distance between the actual and estimated positions of the impact point. (Ref. 55, 56). The required accuracy depends on the application. For example, video conferencing systems that track active speakers require lower localization accuracy compared to autonomous cars, where localization has a direct effect on passengers' safety. Commonly used models are Time Of Arrival (TOA), Time Difference of Arrival (TDOA) and Received Signal Strength (RSS) (Ref. 43, 57–64). Each model has its strengths and limitations. However, we concluded after a thorough investigation that none of the existing models can satisfy our requirements in VibroAware, as discussed in section 1. So, we developed our customized technique (ARSS) to answer our needs. Next, we explain the reasoning behind our decision through a quick review of the commonly used models.

Localization based on TOA or TDOA estimates the position of the impact point based on the propagation speed of vibrations traveling from the impact point to sensors. TOA and TDOA have high accuracy, so they are used in many applications (Ref. 43, 57, 58), including vibroacoustic sensing (Ref. 10). TOA requires having active sources that record timestamps of the impact event to measure the vibrations' propagation time accurately (Ref. 43). So, it is common to see users attach devices to their fingers that record impact events. VibroAware is a passive system that does not require attaching devices to users, so we cannot use TOA. Meanwhile, TDOA does not require timestamps because it measures the difference in propagation times for vibrations at multiple sensors rather than absolute times (Ref. 59–61). However, it requires all sensors to be synchronized, making it prone to mismatches between sensors and common non-idealities in hardware. Additionally, TOA and TDOA require prior knowledge of the waveforms propagation speeds for successful localization (Ref. 43). The speed of sound is assumed when signals are traveling in free space, such as in wireless communication. But when signals are traveling through multiple mediums, such as a sheet of paper on a surface, estimating the propagation speed adds an undesired complexity to the system. That is why systems based on TDOA usually include the surface's material and properties in their computations, and perform complex calibrations based on signal segmentation for each type of vibration waveform produced and its various characteristics (Ref. 10).

RSS is a localization model that measures the power of the received waveform to localize the impact point. RSS is usually used in applications that have lower accuracy requirements (Ref. 43). The power P_i received at sensor i is modeled as $P_i = G_i P_t {d_i}^{-\alpha}$ (Ref. 43). G_i is the amplification factor of the circuit connected to sensor i and amplifies its output. G_i is designed to be identical for all amplifiers in the system. In reality, however, it is common to see amplifier gains suffer from shifts that lead to computation errors. P_t is the vibration's original power at the impact point on the sheet, and d_i is the distance between the impact point and sensor i. α is the path loss constant, which is the rate at which the vibrations' power decays over distance once they start traveling on the sheet's surface. α depends on the medium, such as the sheet's material or the way it is attached. Unless waveforms are traveling in free space, it is tricky to estimate α in advance (Ref. 43). Note that in contrast to TOA and TDOA, RSS does not require prior knowledge of the waveforms propagation speeds.

One means of reducing the number of unknown parameters in RSS is implementing a differential version. Differential RSS (DRSS) calculates the power ratio of waveforms received at two sensors to estimate the position of the impact point (Ref. 43). The formula for the ratio of received power at sensors i and j is $\frac{P_i}{P_j} = \frac{G_i P_t {d_i}^{-\alpha}}{G_j P_t {d_j}^{-\alpha}}$, where P_j is the power received at sensor j, G_j is the amplification factor of the circuit connected to sensor j and amplifies its output, and d_j is the distance between the impact point and sensor j. Notice how DRSS eliminated the need to know P_t, the vibration's original power at the impact point because it is identical for all sensors. By taking the log of both sides, we finally get to:

$$log(\frac{P_i}{P_j}) = log(\frac{G_i}{G_j}) - \alpha log(\frac{d_i}{d_j}) \tag{1}$$

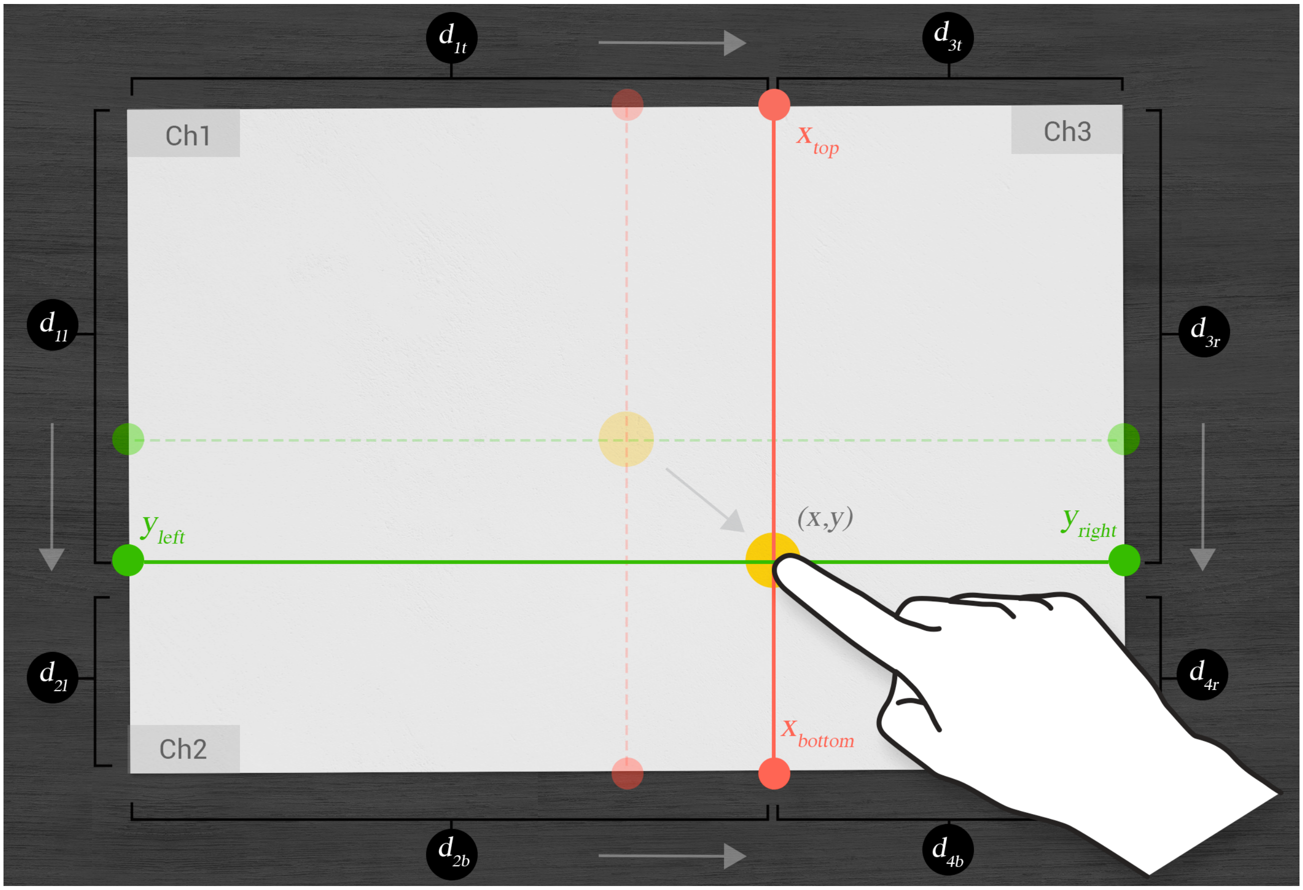


Figure 6. We use source localization to estimate the position of the contact point on a sheet of paper to enable paper-based interaction.

Equation (1) shows a linear relationship between $log(P_i/P_j)$ and $log(d_i/d_j)$. We calculate d_i/d_j based on the measured value of P_i/P_j, assuming that we, hypothetically, know the exact value of α, G_i and G_j. Each sensor pair in the system has its own d_i/d_j ratio that points to a circle on which the impact point is estimated to be (Ref. 65). Ideally, the intersection of all circles that result from each sensor pair in the system is the impact point. In reality, however, because we rely on estimates for α, G_i, and G_j, we end up with multiple intersection points that make the result ambiguous (Ref. 65). Moreover, reflections, refractions, and diffractions of vibration signals make waveform components combine either constructively or destructively at each sensor, leading to measurement errors (Ref. 43). Other factors include random errors, such as static and dynamic noise in the system and environment.

Systems based on RSS and DRSS techniques usually try to overcome these problems by resorting to statistical models, which makes computations complicated (Ref. 65). They also resort to heavy calibrations and pre-training data (Ref. 43), but that shifts the burden to the user and makes the system less practical. We developed ARSS to address these issues, as we explain next.

We developed ARSS based on the RSS model. However, ARSS does not rely on statistical models or pre-training, and does not require information about the medium. That is because ARSS adds correction factors to equation (1) to eliminate the need to know α in advance, which is a function of the material and physical properties of the sheet and the surface. Correction factors also balance shifts in amplification gains due to either hardware non-idealities or tightness imbalances between sensors. Moreover, they help the system adapt to environmental noise, such as pre-existing vibrations of the surface in the room, and minimize its effect. We explain next the concept behind ARSS and show its experimental results.

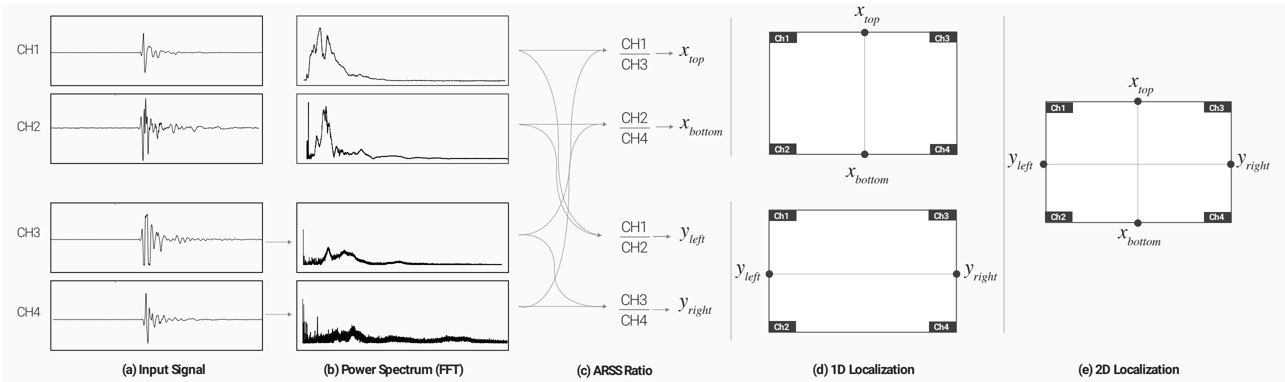


Figure 7. Adaptive Received Signal Strength (ARSS) localization technique. We calculate the x and y coordinates of the contact point by taking the ratio of power between channel-pairs on each edge of the sheet. Our localization point is the intersection of the vertical line between x_{top} and x_{bottom}, and the horizontal line between y_{left}, y_{right}.

In VibroAware, users can attach four sensors on a sheet of paper, as we show in Figure 5. The top left sensor is CH1, the bottom left is CH2, the top right is CH3, and the bottom right is CH4. Each sensor is connected to an amplifier circuit that amplifies its output and sends it to an audio interface. The audio interface receives signals from all sensors, each arriving on a separate channel, and sends them to a computer. We then compute the FFT for each channel to calculate its total power over the full frequency range and localize the impact point. As we show in Figure 6, the impact point, with assumed coordinates x and y, is the intersection point between the vertical and horizontal lines. The vertical line connects x_{top} and x_{bottom}, and the horizontal line connects y_{left} and y_{right}. x_{top} and x_{bottom} are the projections of x on the top and bottom edges of the sheet, and y_{left} and y_{right} are the projections of y on the left and right edges of the sheet. We find the projection coordinates x_{top}, x_{bottom}, y_{left} and y_{right} by comparing the power measured between every two channels on the edge of the sheet (a channel pair).

To elaborate, let us look at Figure 7 and take x_{top} as an example. We calculate x_{top} by comparing the power ratio between CH1 and CH3 on the top edge of the sheet. Based on equation (1), we find that:

$$log(\frac{P_1}{P_3}) = log(\frac{G_1}{G_3}) - \alpha log(\frac{d_{1t}}{d_{3t}}) \tag{2}$$

P_1 is the power of CH1, P_3 is the power of CH3, G_1 is the amplification factor of CH1, G_3 is the amplification factor of Ch3, d_{1t} is the distance between x_{top} and CH1, d_{3t} is the distance between x_{top} and CH3, as shown in Figure 6. When G_1 and G_3 are, theoretically, equal, then $log(\frac{G_1}{G_3}) = 0$. If the measurement shows that $P_1 = P_3$, then $d_{1t} = d_{3t}$, and we conclude that x_{top} is exactly in the middle of the edge between CH1 and CH3. x_{top} is expected to be in this middle position whenever $P_1 = P_3$, which happens when users are not interacting with the sheet (channels carry noise only), or when the x coordinate of the impact point is in the middle of the sheet. If $P_1 > P_3$, then $d_{1t} < d_{3t}$, and we conclude that x_{top} is closer to CH1 rather than CH3. When $P_1 < P_3$, then $d_{1t} > d_{3t}$, which means that x_{top} is closer to CH3 rather than CH1. The same concept applies to x_{bottom}, y_{left}, and y_{right}, as shown in Figure 7. In practical scenarios, however, the same problems of RSS still exist. We still need to know $alpha$ that depends on the material properties, and there are many factors that may lead to inaccurate results, such as unpredictable shifts in amplifier gains, noise in the environment, and sensors with unbalanced tightness when attached to the sheet. This causes unpredictable shifts in x_{top}, x_{bottom}, y_{left} and y_{right}, and eventually in the final x and y computed.

We solved these problems by making ARSS adaptive after adding correcting factors to the equation. As soon as users attach sensors to the sheet, ARSS checks the positions of all projection coordinates x_{top}, x_{bottom}, y_{left} and y_{right}. Each of these coordinates is expected to be in the middle of its corresponding edge during system standby. ARSS records any shifts in their positions during standby and automatically reverses them back to their ideal location by including a correction factor in the calculations. In other words, ARSS changes equation

(1) to:

$$log(\frac{P_i}{P_j}) = log(\frac{A_i G_i}{A_j G_j}) - \alpha log(\frac{d_i}{d_j}) \quad (3)$$

A_i and A_j are the correction factors ARSS applies for channels i and j, respectively. ARSS measures the power in each channel and then selects a value for A_i and A_j that keeps $log(\frac{A_i G_i}{A_j G_j}) = 0$ always, to balance the common shifts in amplification gains and avoid the need to know α in advance. Shifts in amplification gains also represent any tightness imbalances between sensors. The correction factor also accounts for environmental noise, such as surface vibrations underneath the sheet or room noise that may end up in the system. As a result, ARSS adapts by keeping the impact point in the middle during standby. It then keeps using the recorded values of A_i and A_j in all subsequent calculations to minimize errors when users interact with the sheet.

Note how ARSS estimates the impact point's position using lines instead of the circles used in RSS. We are leveraging the fact that the impact point is restricted to be on the sheet confined between all sensors to make such approximations. This makes calculations simpler and more straightforward. And while we had doubts that this may affect the accuracy, we experimentally confirmed that it is still high enough to enable paper-based interactions, as we explain next.

3. EXPERIMENTAL VALIDATION

3.1 System Calibration

VibroAware requires two types of calibrations, both of which are quick and straightforward, compared to complex calibrations usually needed in vibroacoustic systems (Ref. 10, 42, 43). The first is the adaptive calibration. This is an automated process (takes 10ms) to compute correction factors. It is needed when users attach a sheet for the first time, the size of the sheet has changed, or the sheet is moved off sensors. We performed this adaptive calibration, which is fully automatic and does not require user intervention, only once before we began the system's evaluation.

The second is area calibration. This aims to map the interactive interface's size by tapping the four corners of the sheet. This calibration is needed when users attach a sheet for the first time, or when the size of the sheet has changed. We found this calibration to be stable for months after.

3.2 Localization Experimental Results (ARSS vs RSS)

The core ARSS is localizing the discrete touch in real-time. Further interactions the system enables are based on this localization results. For example, when tracking swipes, the system keeps track of the moving impact by computing the difference in consecutive localization results and calculating the corresponding displacement. So we designed an experiment to evaluate the accuracy of discrete touch localization using a printed test sheet with square grids. Based on the average human finger size and dimensions of the sheet, we decided to divide the grid into 70 squares. We attached the sheet to VibroAware and aligned it with an overhead camera as we show in Figure 8a. We created a custom evaluation software that shows an array of squares aligned with the ones on the test sheet as shown in Figure 8b. When ARSS detects a touch, it localizes its position and sends that information to the evaluation software. The evaluation software computes the localization error distance (RMS) by calculating the difference between the localized position of the touch and its actual position as shown in Figure 8c. We decided to repeat the experiment 20 times for each square because the average error distance saw negligible change after that number.

We tested our system under three different settings using both the conventional RSS and ARSS to compare and check the accuracy of the system. For the first two settings, we measured the error distance for each square by touching it on the sheet and recording the result. The first setting uses identical amplifier gains (G1=1, G2=1, G3=1, G4=1) to observe how each algorithm behaves in near-ideal conditions. The second setting uses tampered amplifier gains (G1=3, G2=1, G3=2, G4=1) to observe the behavior in non-ideal conditions. In the third setting, we observed how each algorithm adapted by tampering the gain on each sensor separately. Unfortunately, the authors had to perform the evaluation by themselves due to limited access to participants.

We summarize testing results in Figure 9. When using identical amplifier gains, the average error distance for the conventional RSS was 3.62cm, but it dropped to 1.48cm when we used ARSS, as we show in Figure 9b.

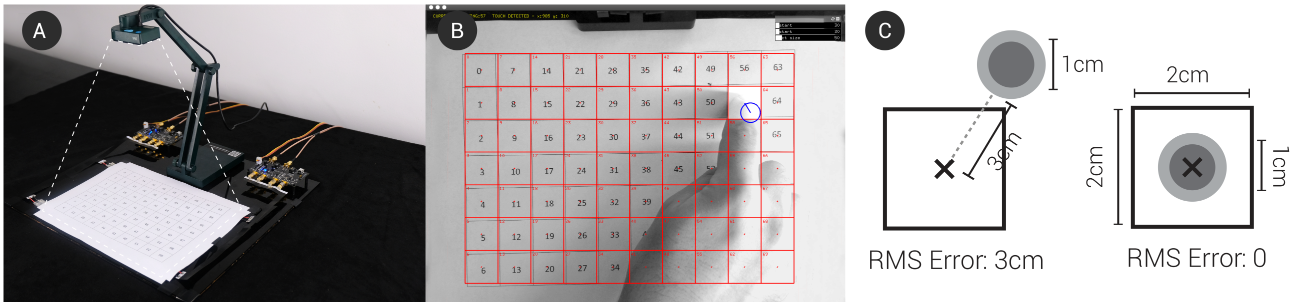


Figure 8. The procedure of technical evaluation. (a) VibroAware setup with printed 20cm x 14cm sheet printed with seventy 2cm x 2cm cells aligned with an overhead camera. (b) Evaluation software displaying the view from camera and alignment between printed test sheet and software grid. (c) Criteria for measuring touch accuracy for each cell.

With tampered gains, the conventional RSS saw 55% increase in the average error distance to reach 5.66cm. However, ARSS was able to adapt and limit the increase in the average error distance to 6%, to reach 1.58cm, as we summarized in Figure 9c. That is 72% improvement over the conventional RSS under the same settings.

The results of the third setting explains how ARSS was able to adapt, as we show in Figure 9a. Whenever we tampered the gains while using the conventional RSS, the impact point's position as calculated by the system (blue dots) shifted towards the channel with the highest gain. For example, when the normalized gains were (G1=3, G2=1, G3=1, G4=1), the system shifted the impact point's position during standby towards CH1 (the figure shows one blue dot for each repeated measurement). So, if users interact with the sheet at that state, the average error in conventional RSS will increase. On the other hand, when we tampered the gains while using ARSS, the system was able to adapt and kept the impact point's position during standby (orange dots) around the middle of the sheet for each gain value. That is because ARSS calculates correction factors for each case and applies them. Hence, the smaller average error. We should mention that the number of evaluation points is the same for both RSS and ARSS, but ARSS's points are clustered because ARSS was able to adapt when we tampered the gains.

It is important to note that thanks to ARSS, evaluation shows that the system works without the need to include information about the medium in our computations, such as vibration propagation speeds, material properties, sheet material and thickness, surface type, frequency responses or other aspects that require complex analysis of the setup. This satisfies our requirements. When we built our system, we did not have to think about which sheet type to use, how much its thickness should be, or which kind of table to test on. These factors are common to all sensors, and will be canceled out due to the nature of our differential computations as we explained in this section. We understand that systems that use TDOA, do complex signal segmentation and include all that information may have a better accuracy, but our system offers users the ability to test and prototype faster, and create interfaces using vibroacoustic sensing on paper more intuitively.

3.3 Classification Experimental Results

We built a prototype to test classification using VibroAware through a neural network we trained, leveraging distinct characteristics of vibration for each interaction type. We implemented our model using TensorFlowJS (Ref. 66). It extracts features from waveforms using a convolutional neural network and outputs a prediction for each class label. The model's architecture has four convolutional layers and three intermediary max pooling followed by two dense layers using ReLU and Softmax activation functions, respectively. We trained the model using Teachable Machine (Ref. 67) by performing each gesture 40 times per class. We generated the test dataset using the same procedure. We trained our model on four gestures: tapping, swiping, pen and sharpie with 40 samples for each class, and recorded the results in a confusion matrix, as we show in Figure 10. As appears in the figure, VibroAware can successfully classify gestures with 90-99% accuracy.

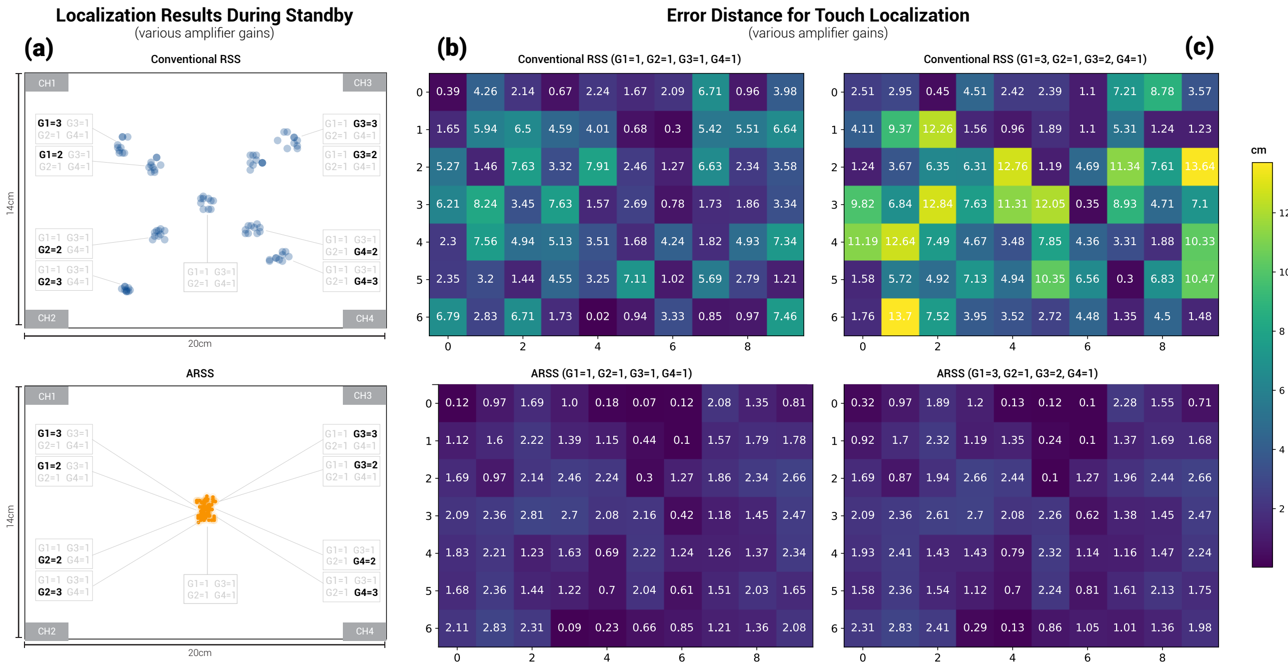


Figure 9. Evaluation results. (a) The impact point's position as calculated by the system during standby under various amplifier gains for the conventional RSS (top) and ARSS (bottom). Conventional RSS shifts the impact point's position towards the channel with the highest gain. ARSS adapted and kept the impact point's position near the middle of the sheet. (b) A comparison of measured error distances between the conventional RSS (top) and ARSS (bottom) when all channels have identical gains. The average error distance was 3.62cm for the conventional RSS, but only 1.48cm for ARSS. (c) The measured error distance when channels have imbalanced amplification gains. The average error distance was 5.66cm (55% increase) for the conventional RSS, but only 1.58cm (6% increase) for ARSS.

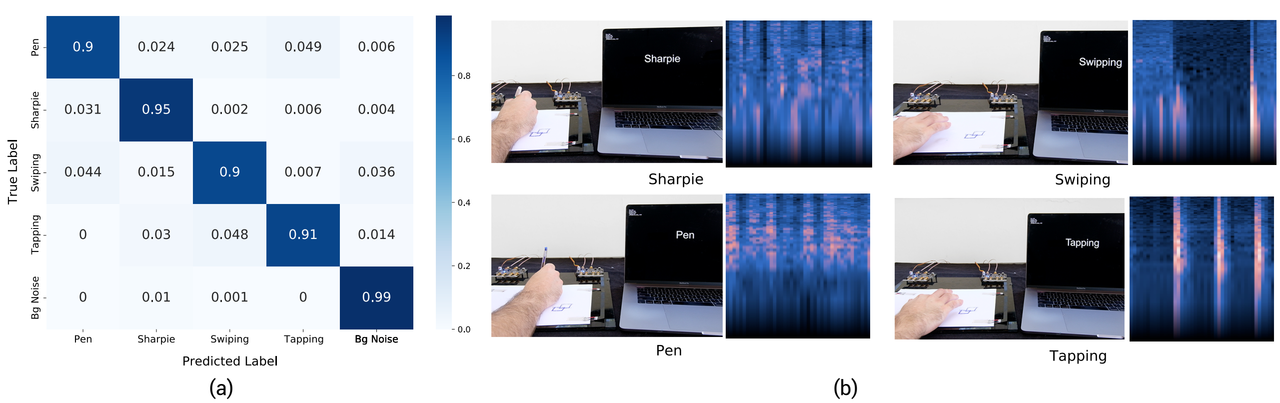


Figure 10. (a) 5x5 Confusion matrix evaluating the performance of our classification model predicting two instruments (pen and sharpie) and two hand gestures (tapping and swipping). (b) Images of interactions performed during evaluation and corresponding audio spectrograms.

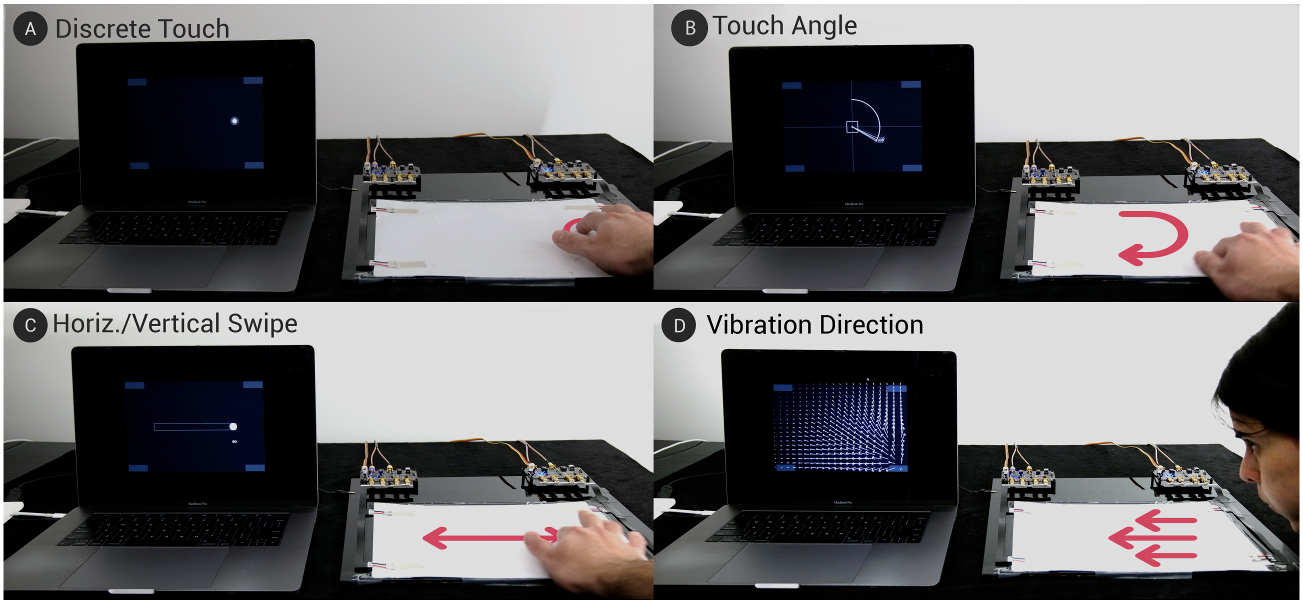


Figure 11. Image of interactions currently supported by our system. a) Discrete Touch b) Touch Angle c) Horizontal/Vertical Swipe d) Vibration Direction.

4. SUPPORTED INTERACTIONS AND APPLICATIONS OF VIBROAWARE

4.1 Supported Interactions

The core of VibroAware is ARSS that allows it to localize discrete touch in real-time, and evaluation demonstrated that it works as intended. Further interactions discussed in this section are based on the localization results ARSS computes.

VibroAware localizes discrete touch in real-time as Figure 11a shows. It can also track swiping vertically or horizontally as Figure 11c shows. When tracking swipes, the system keeps track of the moving impact by computing the difference in consecutive localization results and calculating the corresponding displacement. Enabling swiping gestures allow the paper to be used as tangible extensions to digital functions, such as adjusting sliders, faders and knobs.

VibroAware also tracks the angle of touch on paper as shown in Figure 11b. We achieve this by tracking the coordinates of the impact point on both of the X and Y direction (following x_{top}, x_{bottom}, y_{left}, and y_{right}). For each location in XY, we compute a tangent line that starts at the center of the paper and reaches the target XY coordinate of the touch. This enables the angle to be estimated continuously as fingers move on the paper. We also support contactless interaction such as blowing on the paper's surface as shown in Figure 11d. This allows users to use tools such as speakers or handheld fans that generate vibrations on paper. ARSS uses both touch angle estimation to determine the direction and position of the blowing source.

4.2 Example Applications

In this section, we introduce example applications for VibroAware. Our target is to enable vibroacoustic sensing for a sheet of paper on a surface, so our applications are limited to scenarios where the sheet sits flat on the surface. We set out to explore how attaching sensors to a sheet of paper with instant calibration can rapidly augment existing ubiquitous paper media. We understand that current applications utilize limited paper affordance, but they are intended to define an essential roadmap to instantly augment existing paper media on a surface. We discuss this limitation in detail in section 5. The non-intrusive vibroacoustic sensing on paper, along with the localization and real-time tracking features, allowed us to successfully build several examples, as Figure 12 shows.

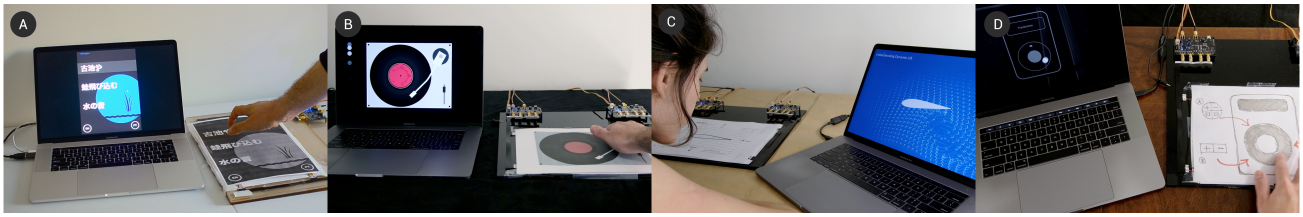


Figure 12. Example applications that demonstrate vibroacoustic sensing on paper. a) Touch to Translate Poster b) Paper Record Scratchin' c) BlowBased Airflow Simulation d) Digital Paper Prototyping.

4.2.1 Touch to Translate Poster

Touch to Translate Poster (Figure 12a) In this example, users touch a printed poster in a foreign language to hear real-time voice translation of the printed content. We developed custom software that maps different locations of the printed poster that trigger audio content to play translations of sentences written in Japanese on the poster to either English or Portuguese. This application demonstrates how ubiquitous paper media (posters, books, magazines) can be instantly augmented with digital information without requiring the media to be instrumented permanently or modified in advance.

4.2.2 Paper Record Scratchin'

Record Scratchin' application shown in Figure 12b). In this application, users control the playback speed of the player by swiping vertically. This enables the record to be 'scratched' back and forth. The speed of the swipe defines the speed at which the record is scratched.

4.2.3 Blow Based Airflow Simulation

This example presents an aerodynamics textbook that visualizes how wind direction can influence the flow of an airplane airfoil (Figure 12c). Users can experiment with scenarios by blowing on the paper to change the wind direction and visualize the effects of wind on different designs of airplane wings. This application demonstrates how an existing media, such as exercise sheets, can become interactive to aid in the learning of complex subjects.

4.2.4 Digital Paper Prototyping

Paper prototyping is a common practice in product and interaction design, as it allows for quick interaction cycles. This application demonstrates the combination of physical paper prototyping with digital functionality (Figure 12d). Gesture controls may be experimentally designed by connecting paper sketches with the functionality. After drawing the sketch of a circular dial, the designer quickly experiments with different gestures such as tapping and swiping to change the volume on the digital prototype.

5. CHALLENGES AND FUTURE VISION

While VibroAware achieves our requirements, we admit that it still faces some challenges. For example, VibroAware does not support multi-touch, has only been tested on a sheet of paper in a flat configuration, and still needs to be tested further on various types and sizes of paper and surfaces. These limitations remain as challenges of adopting vibroacoustic sensing to enable paper interaction on a surface.

We state these challenges clearly to motivate researchers in the community to develop new ideas and overcome the challenges and limitations to enrich tangible interaction with vibroacoustic sensing. We also show the opportunities and challenges of vibroacoustic sensing in paper, as we show in Figure 13. Moreover, we show some of our early prototype ideas for VibroAware in Figure 14. While these early ideas were not thoroughly tested, we believe it is worth showing their potential to the community.

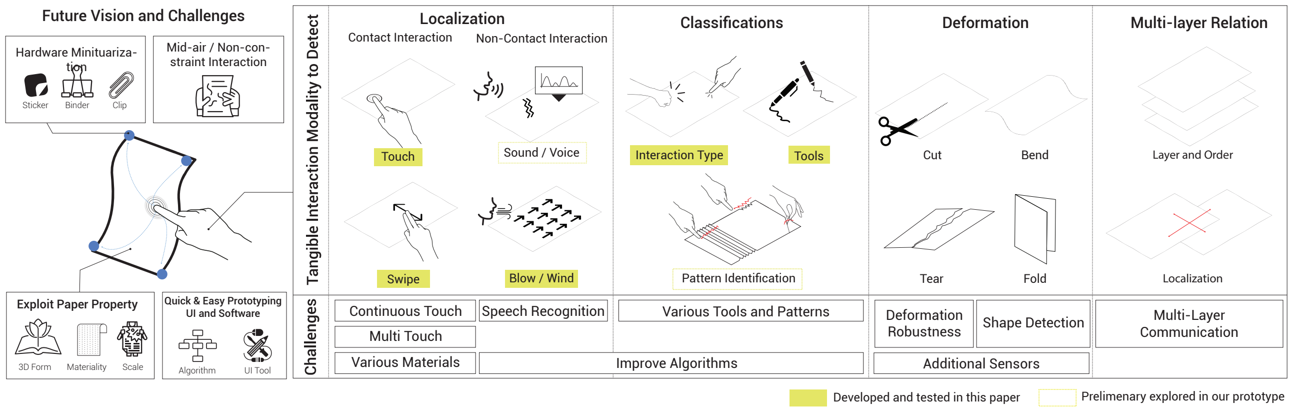


Figure 13. Vibroacoustic sensing on paper: Potential future opportunities and challenges.

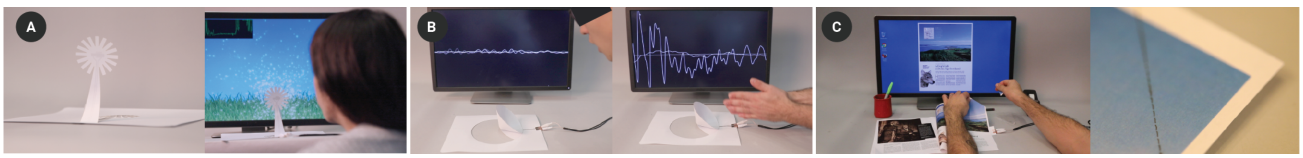


Figure 14. Early Prototypes that explored the open research space of vibroacoustic sensing for paper interaction. (A,B: Detecting blowing and voices with 3D formed paper, C: Detecting tearing interaction on a pre-cut dotted line that generates a patterned sound for action classification.)

5.1 Stationary and Multi-Touch Sensing

As we explained throughout this manuscript, our system currently can only sense interactions that actively produce vibrations, such as swiping. The system is unable to detect stationary touches that do not continuously generate vibration (e.g. resting a finger on the sheet without moving), as vibrations eventually fade with time. We can address this issue in future work by detecting when fingers move away from the sheet after making contact and analyzing the vibrations signatures generated then. In addition, the system is unable detect simultaneous multi-point interaction, which is a common issue in vibroacoustic sensing system. We will investigate this issue in future work by extracting more vibration features to detect multiple peaks in the power spectrum of each signal that may hint at multi-point interaction.

5.2 Hardware Miniaturization

In the current form, the hardware is relatively large and still needs an external power supply, which limits the portability of the system. We envision a version that has miniaturized integrated microchips as small as dots that users can attach to the corners of the sheet to make the system portable. Such small modular system leads to an improved form factor that allows using paper clips or stickers to easily make the sheet interactive, and it can remove the limitation of using our system on a flat surface. We envision arriving at a level where users lift the sheet in mid air to take advantage of its flexibility and light weight, while the system is able to localize interactions in mid-air and unconstrained bi-manual holds or deformed shape. Future work can also improve the system to make it go into deep standby and wake up whenever users attach a sheet to sensors, and perform the calibration automatically.

5.3 Further Paper Interaction Opportunities and Challenges

In this research, what we have explored so far is only a fraction of the many possibilities of paper interaction using vibroacoustic sensing. While ARSS works without the need to include information about the medium in our computations, such as paper material, thickness or surface type, our evaluation is limited only to the standard paper type commonly available at homes and offices. We still need to expand our evaluation to different types and sizes of paper and surfaces to better understand the capabilities and limitations of our approach. We also see that it is worthy to test our system on 2D and 3D forms of paper (Figure 14a,b), to study the limitations of scalability.

Such future work can allow further investigation of the open research space to detect interactivity with minimal, temporal and ad-hoc sensing elements. The possible future interactivity of paper with acoustic sensing includes non-contact interactions such as voice and sound detection and paper that 'listens' (Figure 14b). We can utilize interaction classifications to detect and identify a broad set of interactivity on paper including different ways of touching (Ref. 3) or scratching the papers' surface across a certain physical notched pattern (Ref. 4). We can extend this technique to detect tearing at the perforated line of a paper and generate a distinct sound to be identified by classification (Figure 14c).

One of the primary features of paper is its flexibility and deformable interactions. It may be challenging for vibroacoustic sensing to detect deformable interactivity such as bending, cutting or tearing. However, we can embed additional sensors to the system to detect deformation, such as accelerometers for multi-modal sensing (Ref. 68). Finally, we can use active sensors to enable multi-layer interaction, in which sensors can communicate with each other.

6. CONCLUSION

This research presented VibroAware to demonstrate how vibroacoustic sensing can enable tangible interaction with a sheet of paper on a surface. VibroAware makes the sheet interactive using vibroacoustic sensing by leveraging vibrations, an inherent material property. The sheet's material is preserved by using a non-intrusive and reversible approach that is compatible with existing media by avoiding pre-fabrication. VibroAware offers users the ability to test and prototype faster, and create interfaces using vibroacoustic sensing on a sheet of paper more intuitively. The algorithm developed enables localization and adapts to environmental noise without requiring prior knowledge of vibration propagation speeds or material properties. Sensors with minimal sizes are used to offer users the maximum area for interaction. As a result, VibroAware supports touch, swipe, and contactless interactions such as blowing on the sheet's surface. It can also classify multiple gestures based on the distinct features in vibrations.

VibroAware is a step forward to explore an open research space, with many challenges to overcome. We hope this work opens a new path for future research to explore vibroacoustic sensing and enrich tangible interaction with new ideas to overcome the challenges.

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