

Multitouch Touchscreen using Reverberant Lamb Waves

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Abstract—Touchscreen sensors are widely used in many devices such as smart phones, tablets, laptops, etc., with diverse applications. We present the design, analysis, and implementation of an ultrasonic touchscreen system that utilizes interaction of transient Lamb waves with objects in contact with the screen. It attempts to improve on the existing ultrasound technologies, with the potential of addressing some of the weaknesses of the dominant technologies, such as the capacitive or resistive ones. Compared to the existing ultrasonic and acoustic modalities, among other advantages, it provides the capability of detecting several simultaneous touch points, and also a more robust performance. The localization algorithm, given the hardware design, can detect several touch points with a very limited number of measurements (one or two). This in turn can significantly reduce the manufacturing cost.

Index Terms—ultrasonic touchscreen, ultrasound, Lamb waves, piezoelectric transducers, multi-touch localization, learning method, training method.

I. INTRODUCTION

Touchscreen sensors are widely used in many devices such as smart phones, tablets, laptops, etc. There are many different types of modalities that enable sensing the touch. The dominant technologies on the market are the capacitive, resistive, acoustic or ultrasound, and optical touch systems. None of these technologies are perfect and each has some advantages and disadvantages. Overall, the main difficulties of the current touch technologies are the cost of manufacturing, complexity of the hardware/software, power consumption, and multi-touch capability. These have impeded their widespread applications for large screens.

Capacitive touch technologies are the most common in the industry. However, they suffer from hardware complexity, high manufacturing cost, and high power consumption. They work based upon conductivity of the touch object; so, any non-conductive object cannot be sensed [1]. The mainstream ultrasound touch technologies are surface acoustic waves (SAW) [2], acoustic pulse recognition (APR) [1], [3], and dispersive signal technology (DST) [1]. The main advantages they offer are simplicity in hardware and low manufacturing cost. They operate based on utilizing surface acoustic (SAW) or bending waves (APR and DST). Despite the advantages, they share less than 1% of the market. Surface acoustic waves are highly leaky (into the adjacent medium) or highly attenuating along the path of propagation, thus making SAW technologies extremely sensitive to any surface contamination. Bending wave technologies are more robust. However, they require a tap,

thus a high activation force, to produce enough bending waves to be detected. Overall, ultrasound technologies mainly suffer from lacking robustness (i.e., sensitivity to environmental, mechanical, and thermal noise), multi-touch capability, and smooth touch response, making them uncompetitive to analog resistive and capacitive ones.

We present a summary of the design, analysis, and implementation of a multitouch ultrasonic touchscreen system. It attempts to improve on the existing ultrasound technologies. We present localization algorithms that can detect several touch points with a very limited number of measurements (one or two), using a learning (training) based technique. For more details see [4].

II. GOVERNING PHYSICS

The basic governing principle revolves around the propagation of guided elastic waves in a bounded space such as a plate (e.g., a glass screen). One feature it heavily relies on is the propagation of Lamb waves in the screen and their leakage upon interfacing with a field-perturbing object (such as a human finger). The second feature is the longtime behavior of reverberating Lamb waves in the screen.

Lamb waves propagating adjacent to a fluid can leak depending on the velocity of propagation relative to the surrounding medium such as a human finger. A glass plate and human finger have a significant impedance mismatch with air. Lamb waves can also leak into air, however, with much less efficiency. This principle makes a human finger (or any object with a close acoustic impedance) create a much more pronounced effect on the Lamb waves compared to the surrounding environment such as air. This property lays out a key feature for a human touch to perturb the Lamb waves upon interfacing with the glass screen.

Wave propagation in enclosures can lead to mixing of the wave energy, ultimately leading to an incoherent spreading of information. This is the manifestation of a reverberant field, which makes the localization problem very challenging. Reverberant fields in enclosures can potentially carry useful information, however, in an incoherent way. However, spreading of the wave energy in a reverberant field can lead to multiple interrogations of each point in the enclosure. This suggests that, upon registering a longtime response of the system at only a few fixed locations in the domain, any substructural changes in the enclosure can be sensed with sufficient information carried by the wave energy flow.

This suggests a system consisting of small transducers integrated with a plate. The transducers are pulsed selectively and repeatedly to create propagating Lamb waves inside the plate. The field is then measured at a selection of the transducers (which can include the transmitters as well). Upon having a touch, a local perturbation is created at the touched region, and hence, a portion of the wave field is absorbed through the touch(es). This absorption modulates the registered data in a random way, corresponding to different touch locations.

III. DESIGN AND PROTOTYPING

Through studying the forward physics of the system [5], it became apparent that the lowest order symmetric mode, abbreviated as S0, is advantageous over other modes for the application of interest. Even though the lowest order asymmetric mode, known as A0, has a greater leak rate, for the problem in hand, sustaining the field reverberations for a long time-window is key. Therefore, it is desired to have a gentle touch sensitivity in order to ensure that the touch moderately leaks the wave energy and in long time. Moreover, the S0 mode is faster, and hence, has the potential of setting up the reverberant field faster. Furthermore, S0 can be robustly and selectively excited using a proper transducer design [6] as described below.

For prototyping, a 20 in \times 12 in 830 μm thick glass plate, as a standard component in manufacturing of tablets [1], was used. The designed transducers are 1.66 mm \times 1 mm \times 0.83 mm PZT-5H cuboid piezoelectric elements, with 1.66 mm being the dimension governing the ideal thickness-mode resonance. They have the ideal resonance frequencies at 1.38 MHz, with around a 35% bandwidth. Two opposing surfaces perpendicular to the crystal polarization were metalized. The bonding configuration of the longitudinal transducer will be the determining factor in the selective excitation of the S0 mode. The proper S0 configuration is schematically depicted in Figure 1. This design will lead to the predominant propagation of S0 waves with a typical wavelength around 4 mm. The dimensions of the piezoelectric transducer were chosen such that it operates at the thickness mode resonance with minimal coupling of the lateral modes and a uniform radiation pattern.

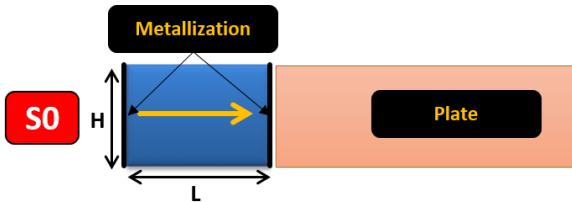


Fig. 1: S0 bonding configuration, realized by attaching the longitudinal transducer to the edge of the screen.

The design has been prototyped by the Microfab Shop of the Stanford Nano Shared Facilities (SNSF) at Stanford University. A prototyped touchscreen is shown in Figure 2.

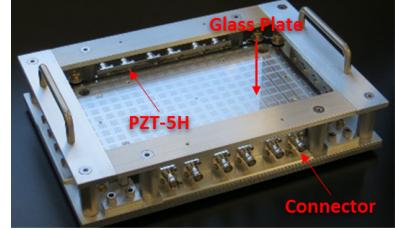


Fig. 2: A fabricated touchscreen prototype.

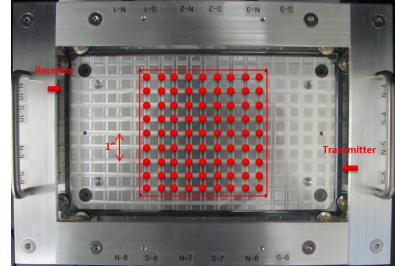


Fig. 3: In-lab implementation of the learning algorithm.

IV. LOCALIZATION ALGORITHM

We propose a learning (training) method to localize the touch contacts. The learning method provides a black-box treatment of the system, implying that the entire algorithm can be implemented experimentally. The learning method, upon an experimental implementation, consists of two steps.

A. Training step

For a given transmit-receive pair, the screen is touched using an ultrasound-absorptive phantom (i.e., a material with an acoustic impedance close to that of a touch object such as a human finger) over a set of points arranged over a rectangular grid. The corresponding signals are acquired and stored in a hard-drive. The size of the phantom as well as the system parameters such as the sampling rate, number of acquired samples, and spacing between the training points depend on the size of the screen, frequency content of the input, accuracy and resolution of interest. After storing the raw signal, several processing techniques are performed including, but not limited to, filtering. The training waveforms as column vectors are stacked together in a $N_t \times N_c$ matrix \mathcal{M} , where N_t is the number of acquired time samples and N_c is the number of training points (i.e., spatial samples). The training waveforms construct a training set.

B. Localization step

Upon having a touch interaction, the measured signal at the receiver undergoes a similar signal processing to that of the training set. The measured signals are then corrected for the drift and noise of the system (see [4] for more details). The training data are looked at as *bases* for a vector space spanned by the training set and localization attempts to find the projection of an arbitrary measurement in that space. Consider the operator \mathcal{M} as a matrix with N columns and infinite rows (experimentally very large, $\approx 10^5$); i.e., a matrix with

the reference measurements as the columns. Let $\delta\mathbf{d}(t)$ be a measurement, and $\mathcal{D} = \text{span}\{\delta\mathbf{d}_i(t)\}_{i=1}^N$. The projection algorithm then reads

$$\min_{\Theta \in \mathbb{R}^N} \frac{1}{2} \|\mathcal{M}\Theta - \delta\mathbf{d}\|_{L^2([0,T])}^2. \quad (1)$$

where $\Theta = (\theta_1, \dots, \theta_N)^\dagger$ and θ_i 's represent the estimated projected coefficient of each touch point, indicating the likelihood of having a touch at that point. When there exist a number of sources and receivers (say N_s and N_r , respectively), we can extend the formulation above to

$$\min_{\Theta \in \mathbb{R}^N} \frac{1}{2} \sum_{r,s} \mu_{r,s} \|\mathcal{M}_{r,s}\Theta - \delta\mathbf{d}_{r,s}\|_{L^2([0,T])}^2. \quad (2)$$

where μ_r 's are the weighting parameters. $\mathcal{M}_{r,s}$ and $\delta\mathbf{d}_{r,s}$ are the data matrix and the measured signal at the r th receiver in response to the s th source. The proposed learning method, upon utilizing the entire reverberant field and longtime data, requires a very limited number of spatial measurements (one or two).

C. Image space algorithm

The performance of the projection algorithm can be improved by adding constraints and reformulating the problem in the image space. The space spanned by all possible configurations of Θ is called the image space, denoted by \mathcal{I} . This algorithm can be implemented as a two-step method:

Step (1): Solve the original unconstrained least squares.

$$\Theta_{r,s}^* = \arg \min_{\Theta_{r,s} \in \mathbb{R}^N} \frac{1}{2} \|\mathcal{M}_{r,s}\Theta_{r,s} - \delta\mathbf{d}_{r,s}\|_{L^2([0,T])}^2. \quad (3)$$

Step (2): Solve a constrained least squares as follows.

$$\min_{\Theta \in \mathbb{R}^N} \frac{1}{2} \sum_{r,s} \mu_{r,s} \|\Theta - \Theta_{r,s}^*\|_{L^2(\mathcal{I})}^2, \quad (4a)$$

subject to

$$\theta_i \geq 0, \text{ for all } i, \quad (4b)$$

$$\mu \|\theta\|_{l^1} = \sum_{i=1}^N \theta_i^*. \quad (4d)$$

μ is a penalty parameter.

V. EXPERIMENTAL RESULTS

A. Experimental setup

Figure 3 represents the in-lab implementation of the explained procedure. The training procedure consists of one transmitter and one receiver. The domain enclosed in the box was chosen as the training domain. A set of grid lines with a half-inch grid-spacing were patterned underneath the glass screen on the Aluminum substrate in order to provide guidance for the training procedure. The screen was then trained on the regions indicated by solid discs, which approximately form a close non-overlapping touch contact areas in the order 0.5 cm^2 covering the entire training domain. This forms a total of 91 training measurements in addition to the data corresponding to the no-touch case. The system was implemented using

a National Instrument NI-PXI5024 digitizer, with a 12-bit vertical resolution. A function generator was used to pulse a S0 transducer, with a 10 V square pulse with a 630 nsec pulse-width. The transmitter at the right edge is pulsed using the function generator and the response is measured at the receiver at the opposite edge. The main lobe of this pulse is band-limited below 2 MHz to assure negligible excitation of the higher order modes. The data were acquired at 50 MS/sec corresponding to a 50 MHz sampling frequency and with a 2 msec time-window, resulting in 10^5 time samples. The localization algorithms were implemented at this sampling frequency.

B. Comparison with the existing algorithms

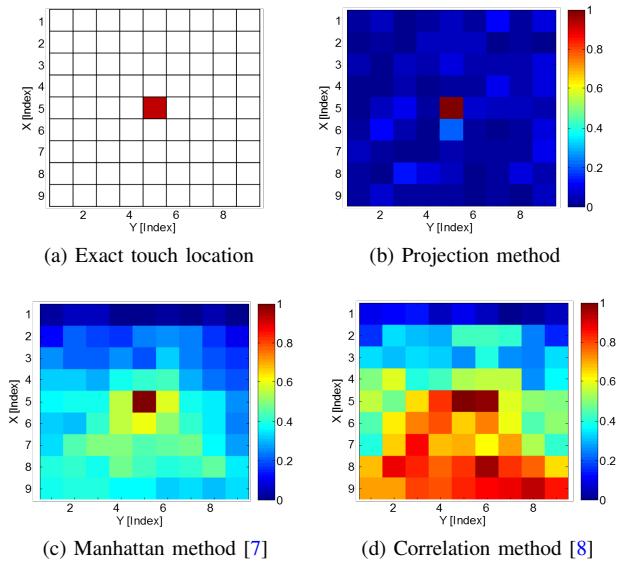
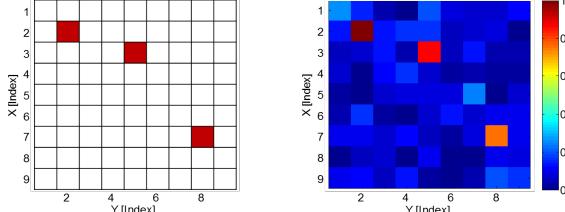


Fig. 4: Comparison of the Projection method with the existing methods for a single-touch test.

Among literature, with a similar detection mechanism, two types of algorithms can be found: the correlation-based localization [8] and localization using the Manhattan (l^1) norm [7], [9]. Applying the projection algorithm, equation 1, a comparison of the three different algorithms for a case of a single touch test is shown in Figure 4 and a three-touch test in Figure 5. The results notably demonstrate a better performance of the proposed method compared to the previous methods.

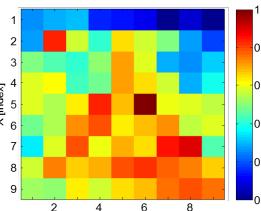
C. Projection vs. image space methods

Increasing the number of the touch points degrades the performance of the projection algorithm, for which case the image space algorithm was presented as the substitute. For a case of five- and eleven-touch tests, the performance of the projection vs. image space algorithms are demonstrated in Figures 6 and 7. We remark that it is very likely that one or several of the test fingers were misplaced. In the worst case scenario, if a finger is misplaced by for example 1/4 of an inch, i.e., half the training grid, the localized touch would be a linear combination for the adjacent points, which will

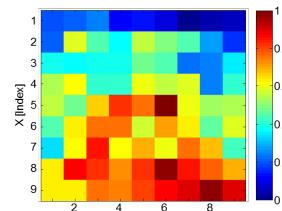


(a) Exact touch location

(b) Projection method

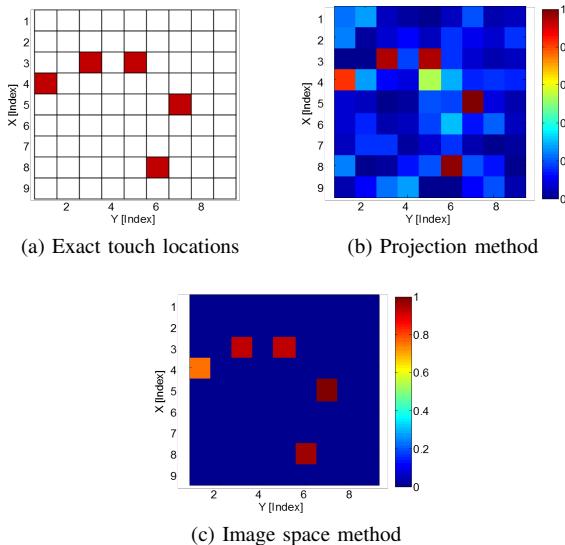


(c) Manhattan method [7]



(d) Correlation method [8]

Fig. 5: Comparison of the Projection method with the existing methods for a three-touch test.



(a) Exact touch locations

(b) Projection method

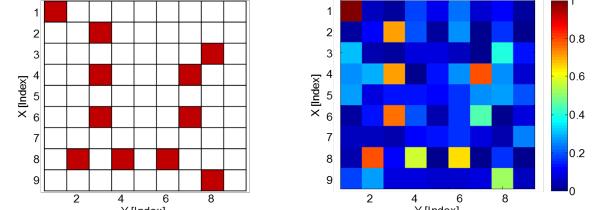
(c) Image space method

Fig. 6: Localization using the projection method vs. the image space method for a five-touch test.

show non-zero amplitudes (high contrast with respect to the background).

VI. CONCLUSIONS

This paper presents a successful design and implementation of an ultrasonic touchscreen system capable of detecting multiple simultaneous touch contacts and with a high touch sensitivity. It attempts to reconcile the benefits of Lamb waves and field reverberation in the screen as the governing mechanism. It relies on the longtime reverberation of the waves inside the screen, where potentially any information induced by a field-perturbing object such as a touch contact interrogates the entire screen several times before reaching



(a) Exact touch locations

(b) Projection method

(c) Image space method

Fig. 7: Localization using the projection method vs. the image space method for an eleven-touch test.

out to the receiver(s). The proposed technology utilizes the minimum number of transducers for a successful localization. Adding more transducers can help improve the quality of the localization. It offers a cost-effective technology with a simple hardware architecture. It is sensitive to any touch object that can reflect or absorb ultrasound such as a finger, gloved finger, pen, etc. It is flexible to support a wide range of screen sizes, from a watch to a projection screen.

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