# Why Piezoelectric Based Force Sensing is not Successful in Interactive Displays?

Challenges towards high detection accuracy.

By Shuo Gao and Linxiao Wu

Piezoelectric based force sensing in interactive displays attracts worldwide attentions due to its intrinsic ability in efficiently converting mechanical energy to electric energy. However, commercialized piezoelectric based products have not been successfully occupying the market, mainly because of the unpleasant detection accuracy. To explain this phenomenon to readers, in this article, we investigate it through finite element analysis. The results reveal that the instable force-voltage responsivity and propagated stress from adjacent force touch locations are two key issues that strongly degrade detection accuracy.

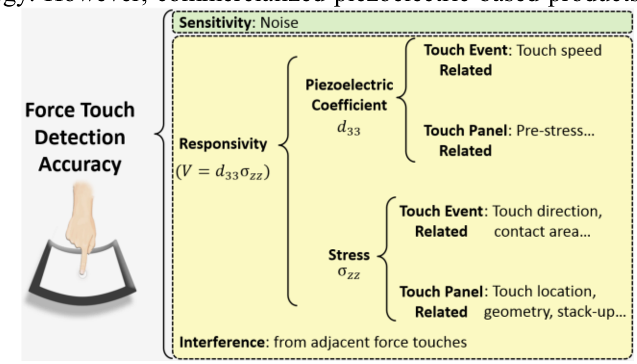



Fig. 1. Piezoelectric material based force touch detection accuracy related facors. Detection accuracy is related with sensitivity (mainly associated with noise floor), responsivity and interference.

## 1. BACKGROUND

Interactive displays have been widely used for a variety of applications [1], and are expected to bring more novel and advanced experiences to customers [2-3] with emerging technologies [4]. One of the most popular interactive displays related consumer electronics is the smart phone [5], which conventionally detects touch activities in 2D by using capacitive or resistive based techniques [1]. Force touch detection is a recent embedded function in smart phones, expanding touch sensing from 2D (x-y) to 3D (x-y-z). Force sensing in touch screen panels (TSPs) is mainly achieved by two means: capacitive [1] and piezoelectric related [6]. In the former, a force touch event increases the capacitance value due to the reduced distance between the electrodes [1]. In the latter, charges are generated due to the force touch induced stress. The magnitude of the charge has a positive linear relationship with the strength of the applied force [6]. Thus the force strength can be deduced by detecting the magnitude of the force induced charge.

Previously reported studies [7-9] demonstrated the strong potential of piezoelectric based touch panels in reaching higher force detection sensitivity compared to their counterparts, due to high piezoelectric $d_{33}$ coefficients [10]. Furthermore, merits such as lower power consumption and less circuitry complexity [7] are also achieved in piezoelectric based force touch panels, since piezoelectric material has the intrinsic ability to convert mechanical stress to electrical signals, hence requiring no extra power source to stimuli the device.

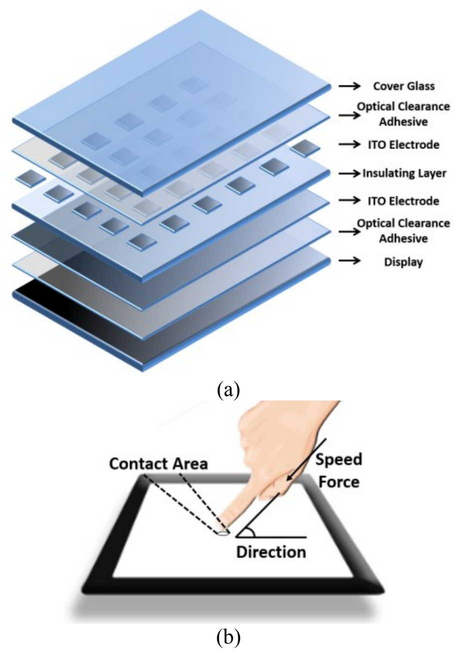



Fig. 2 (a) A typical stack-up of a projected mutual capacitive touch panel. (b) Finger touch's property.

However, piezoelectric based force sensing is not successfully employed in interactive displays yet. Because in force touch panel applications, high force detection accuracy is challenging to achieve. Here, high sensitivity is not directly associated with high detection accuracy, which also depends on stable force sensing responsivity (stable force-voltage responsivity is achieved with different touch events, such as various touch objects and locations.) and elimination of force touch interference (as shown in Fig. 1). An example below is provided to demonstrate this. When the same force touch event occurs at different locations over the touch panel, the force induced stress at the perpendicular angle is not in similar manner, giving rise to different amount of stress induced charges and hence causing the over panel non-uniformity of force-voltage responsivity.

To investigate the issue of low force detection accuracy, in this article, a detailed theoretical analysis together with simulation results are presented. Compared to the conventional means in evaluating detection accuracy by employing sensitivity and signal-to-noise ratio (SNR), work presented here provides an additional road to assess the detection accuracy of piezoelectric based force sensing.

## 2. FACTORS INFLUENCING FORCE DETECTION RESPONSIVITY

### *A. Capacitive Touch Panel Construction and Mechanical Property*

First we describe how a CTP is constructed, in order to explain CTP's mechanical model, which is the foundation of the analysis in this article. Almost all the projected capacitive touch panels share two basic features in their constructions. First the touch surface is above the sensing circuits, and second all the components are fixed which means no moving part in a CTP. A typical two layers projected capacitance construction is conceptually shown in Fig. 2 (a). Two transparent thin-film indium tin oxide (ITO) conductors are separated by a thin-film insulator (normally glass or polyethylene terephthalate (PET), here is where piezoelectric material is embedded), and a touch surface is set on top of them. The four edges of the touch screen are supported by a frame, which is then screwed with the liquid crystal display (LCD) shield.

In the mechanical property analysis, a touch panel can be modeled as a thin plate, as the thickness is far smaller than width and length of the touch panel [6]. The boundary condition of the touch panel is between simple supported and fully clamped, depending on both stack-up architecture and assemble process. Based on the plate theory [11], we can learn that, any change of the panel geometry and mechanical property (e.g. Young's modulus and Poisson ratio) can result in an inaccurate force interpretation.

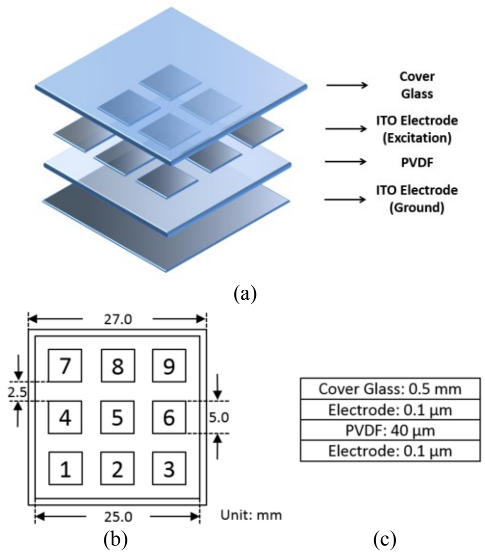



Fig. 3. (a) Structure of simulated touch panel with 9 touch pads; (b) top view of the simulated touch panel and geometries (numbers indicate locations of touch pads); (c) Thickness of layers of the touch panel.

Table I: Parameters of modelled touch panel

| | Young's Modulus (Pa) | Poisson Ratio | Density (kg/m³) |
|---|---|---|---|
| **Cover Glass** | $7.4\times10^{10}$ | 0.3 | 2200 |
| **PVDF** | $3.6\times10^{9}$ | 0.18 | 1780 |
| **ITO** | $11.6\times10^{10}$ | 0.35 | 7120 |

Table II: Parameters of analysis on touch events related influence.

| Parameters | Range |
|---|---|
| Frequency [Hz] | [0,10,100] |
| Radius [mm] | [1,1,5] |
| Direction [degree] | [90,15,30] |

### *B. Properties of Finger Touch Events*

Only finger touch events are discussed here, since finger is the most widely used touch object with smart phones. Finger touch can be analyzed from three aspects: contact area, speed and touch angle, as illustrated in Fig 2 (b). First, the contact area mainly depends on the fingertip's diameter, which is from 7mm to 15mm for children and adults. Second, the finger touch frequency is normally limited within 10 Hz, indicating maximum ten touch events by a single finger can occur in a second. However, the behavior of touch signals is sometimes more close to discrete impulse signals, rather than continuous periodical signals, or static DC signals. The width of force touch induced electric pulse can be at ms level [7]. If the electrical signal induced by a press-and-release touch event is treated as a sinusoidal signal, then the force signal's frequency range can reach up to several kHz range. Hence the frequency of force touch signal could be from DC to kHz range. In the simulation analysis in next section, touch events are assumed as sinusoidal signals, hence frequency is used as a representative of touch velocity. Third, the angle of touch event depends on many factors, such as software applications and user habits. When finger contacts touch panel from different angles, the stress at perpendicular angle can be varied.

## 3. METHOD DESCRIPTION

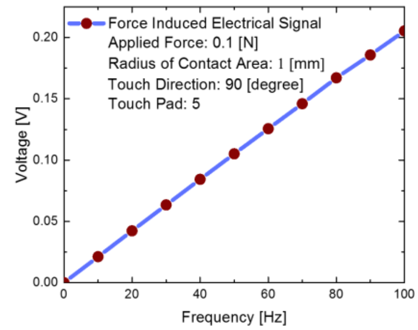
In the previous section, factors influencing force detection accuracy were briefly discussed. For the purpose of conducting a deep and comprehensive analysis, where quantified results are required, a touch panel with 9 touch pads is studied by employing finite element analysis (FEA) method. The touch panel is simulated by the software COMSOL, which is proved to be able to provide precise numerical results [6]. The architecture and geometry of the touch panel are described in Fig. 3. FEA parameters are provided in Table I. Instability of responsivity and force touch interference caused by touch events and touch panel's mechanical property will be demonstrated and explained in detail. In the following section, touch event and touch panel related influences are investigated, respectively.

## 4. RESULTS AND DISCUSSION

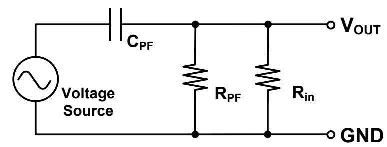
### *A. Touch Signal Property related Effect on Force-voltage Responsivity*

In this subsection, three aspects (frequency, contact area, touch angle) of finger touches are studied. The range of each aspect (parameter) is provided in Table II. When we investigate the effect of one parameter, the other two are fixed. Here, the contact area is assumed to be a circle, hence the contact radius decides the area dimension. In this subsection, finger touches are performed at the center of touch panel (location 5).

First, touch signal's frequency is analyzed. In Fig. 4 (a), it can be observed that, under the same force strength, the force-voltage responsivity boosts with the increment of frequency. The rise of responsivity is contributed by the RC constant of the piezoelectric material and electrodes consisted capacitor and connected readout circuit. The equivalent circuit of piezoelectric based force sensor (derived in [7]) is illustrated in Fig. 4 (b). $C_{PF}$ and $R_{PF}$ are the internal capacitance and resistance of the piezoelectric sensor.



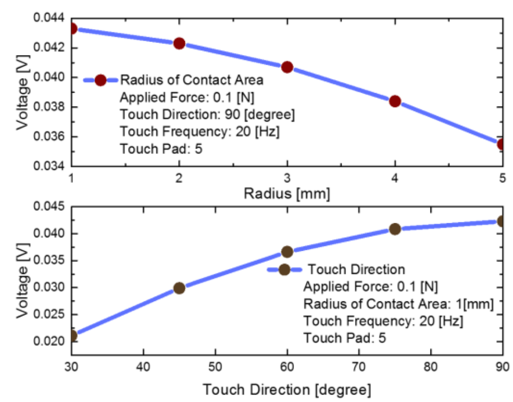

(a)



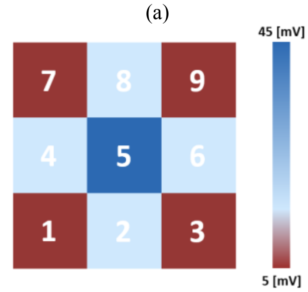

(b)

Fig. 4. (a) Relationship between touch frequency and induced voltage. (b) Equavelent circuit of piezoelectric based touch sensor.

As the resistivity $\rho_{PF}$ is normally huge for piezoelectric materials (e.g. $2\times10^{14}$ Ωcm), $R_{PF}$ is normally much larger than the input resistance of the readout circuit (normally around MΩ level) $R_{in}$, hence can be neglected [6]. From Fig 4 (b), we can learn that piezoelectric sensor's equivalent circuit is a high-pass filter. In our simulation, the internal capacitance is around 55 pF, and the input resistance is 1 MΩ, therefore the RC constant ($\tau$) is around 55 μs and corresponding cut-off frequency is 2.9 kHz, explaining the boost trend of responsivity in Fig. 4 (a). From the thin plate theory [6,11], we can learn that the contact area has a negative correlation with the responsivity, since larger contact area gives rise to smaller stress, decreasing the amount of stress induced electrical signal. In contrast, the touch direction is positively correlated with the responsivity, as more stress in z direction can be obtained when the touch direction approaches to perpendicular. Due to the lack of literature in providing accurate closed-form estimation, numerical analysis is conducted and results are shown in Fig. 5 (a). We can observe that, the responsivity can be shifted up to 22% and 51%, when the radius of touch area increases from 1mm to 5mm and the touch angle decreases from 90° to 30°.




(a)




(b)

Fig. 5. Relationships between (a) radius of contact area, touch direction and force induced voltage; (b) touch location and force induced voltage.

### *B. Touch Panel related Effect on Force-voltage Responsivity*

In the previous subsection, touch signal property related effect on force-voltage responsivity is investigated. In this subsection, the touch panel related effects are analyzed. More specifically, the non-uniformity of force-voltage responsivity over panel scale is studied.

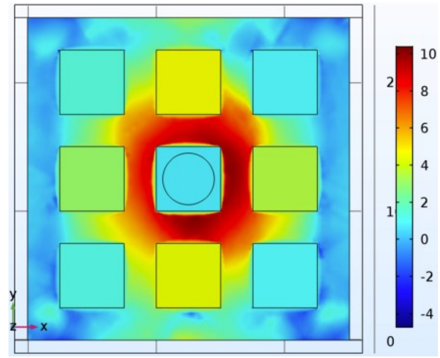
In the simulation setting up, a force touch (in this and next subsections, all the force touches are with the same property: 0.1N, 1 kHz, $4\pi$ mm$^2$, 90°) is applied at center positions from touch pad 1 to 9. The force touches induced voltage amplitudes are depicted in Fig. 5 (b). We can observe that the responsivity at center touch pad is approximately 9 times larger than those at corner touch pads. This is mainly due to the fully clamped boundary condition of the touch panel.

### *C. Propagated Stress Induced Force Touch Mis-registration*

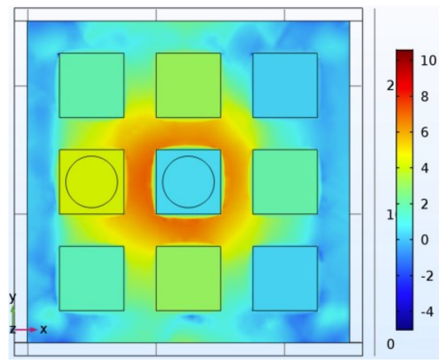
When a force touch occurs, the force touch induced stress can propagate to adjacent locations, and may introduce to fake force touch registrations [7]. In Fig. 6 (a), a force touch is applied at the center of the touch panel, and results in an electrical signal at 70 mV. However, the propagated stress can be even higher than the stress at the touch location, due to the boundary condition of the touch panel. For example, the propagated stress induced voltage at touch pad 4 is 304 mV, which could be interpreted as a force touch signal.

The propagated stress can give rise to more complex issues when multiple force touches happen simultaneously. Fig. 6 (b) demonstrates a case when two force touch events occur at touch pads 4 and 5 at the same time. Compared to the simulation result in Fig. 6 (a), it is learned that the voltage shift at touch pad 5 is 27 mV, decreasing the force touch detection resolution.

The FEA studies in this section reveal and explain the instable responsivity and force interference issues in piezoelectric material based force touch sensing in interactive displays. Based on the numerical results and analysis, we can learn that the strength of force induced electrical signal is highly correlated with characterizations of applied touch event and mechanical properties of the touch panel. Hence, compared to chase higher piezoelectric coefficient, addressing these two key issues deserve a higher priority in enhancing the force touch detection accuracy.




(a)




(b)

Fig. 6. (a) Force touch at the center of the touch panel. (b) Adjacent force touch disturbs the electric output from the center force touch.

## 5. CONCLUSION

In this paper, detection accuracy of piezoelectric film based touch panels in interactive displays are studied from angles of force-voltage responsivity and force interference, which are mainly related to touch events and touch panel's properties. Based on the simulation results, we conclude that, first, the electric output can change dramatically with the same force strength, when other touch related properties (e.g. touch location) are different. Second, the propagated stress can strongly disturb force touch registration in terms of presence and amplitude. The content in this paper is a necessary complementation of previous studies, which focused on improving piezoelectric $d_{33}$ coefficient and system SNR. The presented work advances the successful use of piezoelectric material in interactive displays for force sensing. By explaining and understanding the current challenges, calibration methods can be designed to maintain stable responsivity and remove the influence of propagated stress.

## ABOUT THE AUTHORS

**Shuo Gao** (sg690@cam.ac.uk) is with the University of Cambridge, Cambridge, UK and the University College London, London, UK.

**Linxiao Wu** (linxiao.wu.13@ucl.ac.uk) is with the University College London, London, UK.

## REFERENCESR

[1] A. Nathan and S. Gao, "Interactive Displays: The Next Omnipresent Technology [Point of View]", *Proc. IEEE*, 104(8), pp.1503-1507, 2016.

[2] S. Thavalengal and P. Corcoran, "User authentication on smartphones: focusing on iris biometrics", *IEEE Consum. Electron. Mag.*, vol. 5, no. 2, pp.87-93, 2016.

[3] Y. Yuan, "Changing the World with Virtual\/Augmented Reality Technologies", *IEEE Consum. Electron. Mag.*, vol. 6, no.1, pp.40-41, 2017.

[4] Mohanty, S.P., 2017. Deep Learning Can Be Crucial for Smart Consumer Electronics [Notes from the Editor]. *IEEE Consum. Electron. Mag.*, vol. 6, no. 2, pp.3-4.

[5] A. Berenguer, J. Goncalves, S. Hosio, D. Ferreira, T. Anagnostopoulos and V. Kostakos, "Are Smartphones Ubiquitous? An in-depth survey of smartphone adoption by seniors", *IEEE Consum. Electron. Mag.*, vol. 6, no. 1, pp.104-110, 2017.

[6] S. Gao, V. Arcos, and A. Nathan. "Piezoelectric vs. Capacitive Based Force Sensing in Capacitive Touch Panels", *IEEE Access* vol. 4 pp.3769-3774, 2016.

[7] S. Gao, X. Wu, H. Ma, J. Robertson, and A. Nathan. "Ultrathin Multifunctional Graphene-PVDF Layers for Multidimensional Touch Interactivity for Flexible Displays." *ACS Appl. Mater. Interfaces,* vol. 9, no. 22, pp. 18410-18416, 2017.

[8] T. Vuorinen, et al., "Printable, transparent, and flexible touch panels working in sunlight and moist environments", *Adv. Funct. Mater.*, vol. 24, no. 40, pp.6340-6347, 2014.

[9] Bae, Sang-Hoon, et al. "Graphene-P (VDF-TrFE) multilayer film for flexible applications." *ACS nano*, vol. 7, no. 4, pp. 3130-3138, 2013.

[10] F. Liu, N. A. Hashim, Y. Liu, M. R. M. Abed, K. Li, "Progress in the production and modification of PVDF membranes", *J. Membr. Sci.*, vol. 375, pp. 1-2, June 2011.

[11] M. Touratier, "An Efficient Standard Plate Theory", *Int. J. Eng. Sci*., vol. 29, no. 8, pp.901-916,1991.