LOW ENERGY AND LATENCY TOUCH DETECTION USING GROUP TESTING

Youngchun Kim and Ahmed H. Tewfik

The University of Texas at Austin
Electrical and Computer Engineering
Austin, Texas, USA

ABSTRACT

This paper presents a novel touch detection scheme on a capacitive touch screen with reduced sensing latency and low power consumption. We make use of the fact that a small number of touch sensors have appreciable changes in their capacitance values corresponding to the touch locations; this enables reduction in energy consumption via sensing fewer number of measurements compared to the standard approach. In particular, we use the concept of group testing for designing our touch detection scheme. We demonstrate simulation results confirming that the detection performance of our scheme is comparable to the standard method with significantly lower energy requirement.

Index Terms— binary hypothesis test, group testing, capacitive touch screen

1. INTRODUCTION

Touch screens have become the most popular interface for mobile applications in devices such as smart phones and tablet PCs. The *touch* and *non-touch* inputs need to be sampled and detected using multiple sensor nodes in these applications, while performing tasks like web-browsing, exploring menus, or sending messages. It is desirable that the screen shows a fast response to touch inputs for enhancing temporal resolution and user experience; this motivates the need for a fast touch sensing and detection scheme for improving system response. However, the energy consumption increases linearly as the update rate of sensing increases. Thus, it is necessary that a touch sensing scheme uses a small number of measurements to compensate for the increase in the update rate of sensing. Furthermore, it is known that touch screens consume a significant fraction of the battery power in most of the hand-held devices available at present. Thus, an energy-efficient touch detection scheme is desirable so that the devices can function for longer periods of time.

Standard touch controllers rely on multiplexing the sensor signals using a single analog-to-digital converter (ADC). One solution to improve the temporal resolution is to increase the number of ADCs; however, this leads to increased power consumption, material cost and hardware complexity. The use of compressive sensing (CS) for sensing and reconstructing touch inputs in capacitive touch screens is studied in [1]. It is also shown that the energy consumption can be reduced by sensing multi-channel sparse signals using a single ADC [2]. One can use these methods to reduce the energy requirement for sampling touch-input signals. However, this requires a specially designed modulator for driving voltage, and use of complex algorithms, based on convex optimization or greedy methods, for accurate signal recovery. Therefore, we focus on designing a reliable detection of touch inputs instead of reconstructing them exactly.

In this paper, we design an efficient sensing scheme for detecting touch locations that uses fewer measurements and has reduced energy requirement compared to the standard approach. We show that our scheme detects one- and two-touch inputs leveraging on the concept of group testing and analytical formulation of the touch detection problem.

The remainder of this paper is organized as follows: Section 2 introduces the model for multi-channel touch screen system, describes the standard method for detecting touch inputs, and formulates the touch detection problem as a hypothesis testing problem. We describe the method that requires reduced number of measurements and energy consumption using the proposed scheme based on group testing in Section 3. In Section 4, we compare the energy consumption of the standard and proposed approaches. We finally present the simulation results in Section 5.

2. SYSTEM MODEL

The system set-up, for detecting touch inputs in capacitive touch screens, consists of capacitive touch nodes, capacitance-to-voltage converters (C-to-V), and a single ADC [3, 4]. When a finger touches a screen node, the touch input produces a change in the node capacitance, and the change is sensed by the ADC after a C-to-V converter. To obtain multi-dimensional measurements, the touch screen is sampled by either multi-channel or multiplexed sensing schemes after applying driving voltage (V_{ext}) to each node. We assume here that the capacitance of each node is sampled by multiplexing as shown in Fig.1.

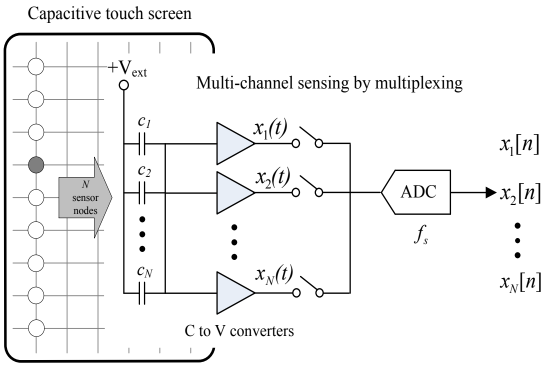


Fig. 1. Multi-channel touch sensing circuit.

2.1. Touch detection

We consider a simplified version of the touch detection problem, namely single-touch detection. We assume that there are N locations that needs to be monitored for capacitive changes. Furthermore, we assume that only one location exhibits a capacitance change. An example of this case is when a user touches the screen with one finger on widely spaced touch sensors. The touch detection problem at each location can be interpreted as a binary hypothesis testing problem. At $t = 0$, under hypothesis H_0, a noisy measurement of the baseline capacitance $x_k(0)$ is generated at location k. At $t = 1$, under hypothesis H_1, a noisy measurement of the change in capacitance induced by the single-touch input is generated. These measurements comprise of an unknown baseline capacitance $c_k(t)$ (for hypothesis H_0 and H_1) and an unknown change of capacitance $s_k(t)$ (for hypothesis H_1) at location k as follows:

$$\begin{aligned} &H_0 : \text{touch is absent,} \\ &\qquad x_k(0) = c_k(0) + n_k(0), \\ &\qquad x_k(1) = c_k(1) + n_k(1), \\ &H_1 : \text{touch is present,} \\ &\qquad x_k(0) = c_k(0) + n_k(0), \\ &\qquad x_k(1) = c_k(1) + s_k(1) + n_k(1). \end{aligned} \tag{1}$$

$n_k(t)$ is a noise process that has zero-mean Gaussian distribution and satisfies $E[n_k(t)n_k(s)] = \sigma^2\delta_{t,s}$, where σ^2 is the noise power density, and $\delta_{t,s}$ is the Kronecker delta function.

2.2. Standard approach

The standard (one-by-one sensing) approach consists of monitoring each location for capacitive changes by subtracting $x_k(0)$ from $x_k(1)$ [3, 4]. By defining $z_k = x_k(1) - x_k(0)$, the binary hypothesis testing is expressed as:

$$\begin{aligned} H_0 &: z_k = w_k, \\ H_1 &: z_k = s_k + w_k, \end{aligned} \tag{2}$$

where s_k denotes the change in capacitance at location k, and w_k is zero mean Gaussian noise with variance $2\sigma^2$. It is known that the change in capacitance s_k is positive unknown variable for each k in capacitive touch sensors with self-capacitance. Our model then is a testing problem with Gaussian data with an unknown positive mean:

$$z_k \underset{H_0}{\overset{H_1}{\gtrless}} \gamma, \tag{3}$$

where γ is a threshold determined by the probability of false alarm. H_0 or H_1 are decided depending on the existence of signal s_k, and this is the best test depending on observations considering the unknown information. The performance of the test is completely determined by the probability error $Pr^{error} = Q(d_{std}/2)$, where $Q(x) = \int_x^\infty 1/\sqrt{2\pi}$ $\exp(-x^2/2)dx$, and $d_{std} = s_k/(\sqrt{2}\sigma)$ in the single-touch case. With this testing scheme, we can decide a touch location from multi-dimensional signals by conducting N binary hypothesis tests. Here, we define the error event as the event that the decision at least one of the N detectors is incorrect; then the probability of error is given by $Pr^{error}_{std} = 1 - (1 - Pr^{error})^N$. Also, the decision process requires N measurements to perform N binary hypothesis tests.

3. REDUCED LATENCY AND POWER CONSUMPTION

3.1. Single-touch detection

We apply the concept of group testing for designing the touch detection scheme to reduce the number of measurements. Group testing was proposed to minimize the collection of tests $M(q, N)$ that needs to detect q defectives out of N universal items [5]. Group testing can be *adaptive* that performs the next test based on the result of current test or *non-adaptive* that decides a test matrix prior to performing tests. Non-adaptive group testing is attractive to design a system because the hardware configuration does not need to be changed regardless of the previous test results. Thus, we describe the proposed sensing scheme that uses the concept of non-adaptive group testing.

3.1.1. Reduced test complexity by group testing

The single-touch detection problem is equivalent to testing a single defective ($q = 1$) in group testing. In group testing, only $\log_2 N$ tests are required to detect a single-touch input from N sensor nodes. Designing the tests, we define an $M \times$

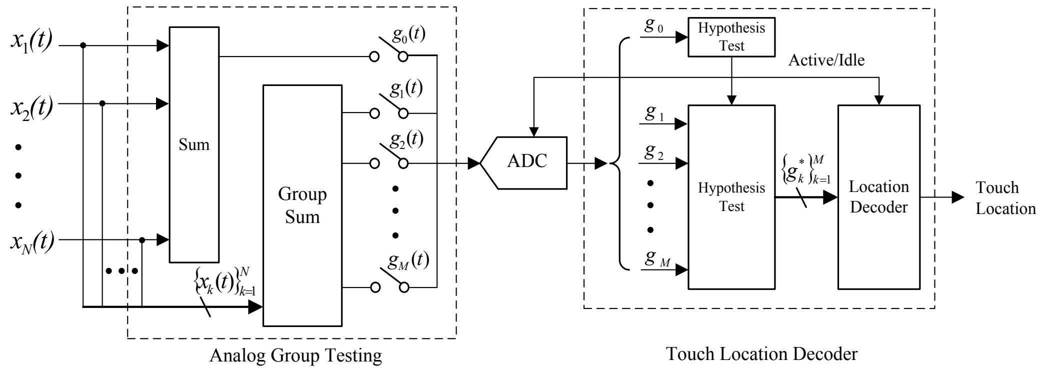


Fig. 2. The proposed sensing scheme with a single ADC. The summing circuit is connected to all N sensor nodes for the change detector, and the group-summing circuit combines sensor signals to produce g_i according to the row vector of the test matrix A.

N test matrix A, where $M = \log_2 N$ as follows:

$$A = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \end{bmatrix}. \quad (4)$$

Group testing produces a measurement vector by a linear operation $\vec{g} = A\vec{x}$. The row vectors of test matrix A produce test results which combine the noisy measurements of the capacitances from the N sensor nodes. If the A(i-row,j-column) entry is one (1), then the j-th sensor signal is summed to the i-th measurement for all $i = 1, 2, \cdots, M$ and $j = 1, 2, \cdots, N$. A zero (0) at the location $A(i,j)$ indicates no connection between the j-th sensor signal and the i-th measurement. For example, if a finger touches the 5-th sensor node when $N = 8$, then the sensor signal is represented in the test vector expressed as $\vec{x} = [x^{(0)}, x^{(0)}, x^{(0)}, x^{(0)}, x^{(1)}, x^{(0)}, x^{(0)}, x^{(0)}]^T$ with a noisy non-touch signal $x^{(0)}$ and a noisy touch signal $x^{(1)}$. By performing binary hypothesis testing $g^* = \{g_i > \eta \mid \vec{g}\}$ for i = $1, 2, \cdots, M$ with a threshold η which is determined by a given probability of error, the touch location is estimated as $g^* = [1, 0, 0]^T$. The location can be simply decoded because the column vectors of the matrix A are linear increasing and the binary estimate g^* indicates the location in a binary value. Thus, a fast decoding is possible using the sensing scheme.

The performance of this approach can be obtained as follows. We have a location error of any decision at any of the $M = \log_2 N$ detectors is incorrect. Thus, the probability of error is given by $Pr_{GT}^{error} = 1 - (1 - Pr^{error})^M$, where $Pr^{error} = Q(d_{GT}/2)$ and $d_{GT} = s_k/(\sqrt{N}\sigma)$. Using the group testing scheme, the temporal resolution is improved by the factor of N/M due to the reduced number of measurements. Therefore, it reduces the sensing latency with the same factor.

3.1.2. Reducing energy consumption by change detection

The energy requirement in touch detection can be reduced by a change detector preceding the structure outlined in the group testing scheme. The change detector is realized by augmenting a row vector which consists of N ones to the test matrix A as below:

$$A = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \end{bmatrix}. \quad (5)$$

The augmented first row is called the change detector, and this is to detect a change in touch-input status. If the change detector shows the null hypothesis H_0 as the test result, then group testing to detect the touch location does not need to be performed. For the same touch signal vector $\vec{x}$ as in the previous example, the new test matrix A produces a $(M + 1) \times 1$ test result $\vec{g} = [g_0, g_1, g_2, g_3]^T = [\tilde{g}^{(1)}, g^{(1)}, g^{(0)}, g^{(0)}]^T$, where $\tilde{g}^{(1)}$ stands for the test result of the change detector, which is the collection of noisy capacitance signals from N sensors when a touch input is present. The touch-input status can be detected by performing a binary hypothesis testing on g_0. If the result shows H_1, then we perform group testing to decode the touch location. If not, we skip group testing. The rest of vector elements, $[g_1, g_2, g_3]^T$, indicate the touch location after performing binary hypothesis testings as in the previous example. In practice, the proposed scheme can be implemented in a readout circuit as shown in Fig.2.

The performance of the change detector is characterized by $\tilde{d}_0 = s_k/(\sqrt{2N}\sigma)$. An error will occur if we miss a change or if we detect the change but make an error in the reduced test complexity described in the previous section. Thus, the performance is given by $Pr_{LOW}^{error} = Pr_{change}^{error} + (1 - Pr_{change}^{error}) \times Pr_{GT}^{error}$, where $Pr_{change}^{error} = Q(\tilde{d}_0/2)$. The theoretical performance of the proposed approach is investigated with respect to the probability of error, and is summarized in Fig. 3. The low energy scheme shows equivalent performance as the standard approach according to signal-to-noise ratio (SNR) conditions, which are affected by the size of N. However, the proposed scheme achieves the performance with improved sensing latency and energy requirement than those of the standard approach. The proposed method uses $\log_2(N) + 1$ measurements for detecting a single-touch location, and requires merely one measurement for sensing N locations simultaneously if the touch input is absent.

The main goal of using group testing is to minimize the ratio M/N by a smart choice of the $M \times N$ test (encoding) matrix A where $M < N$. Generally, the non-adaptive group testing scheme are efficient when N is large and the ratios of q/N very small. However, in the proposed method, N sensors are monitored simultaneously by summing N-node signals together at the change detector. As in Fig. 3, the detection performance can be close to the standard detection scheme when N is small. Thus, the largest possible N should be determined by noise conditions. This is involved in a trade-off between sensing efficiency and accuracy in the detection problem. Thus, we need to decide N which does not degrade the detection performance considering noise conditions according to prior information which is given through experimental analysis. In Fig. 3, we compare the theoretical performances of the standard and the proposed methods with dashed lines if N is equal to 8 and 32.

3.2. Two-touch detection

In pinching gestures to zoom in or out a touch screen, tow sensors are activated by two-finger touches. The scenario is possible when fingers touch widely spaced touch grids. To detect two-touch inputs, a new test matrix is needed, which can accommodate the multi-touch signals without information loss. Two types of matrices, q-separable and q-disjunct matrices, are studied to generate the test matrix A in non-adaptive group testing.

Definition 3.1. *(q-Separable Matrix)* A binary $M \times N$ matrix A is q-separable if the unions of up to q columns of A are all distinct.

Definition 3.2. *(q-Disjunct Matrix)* A binary $M \times N$ matrix A is q-disjunct if the union of less than or equal to q columns does not contain another column.

Generally, a q-separable matrix is more efficient than a q-disjunct matrix in sensing perspective because a q-separable matrix requires fewer tests $M(q, N)$ than q-disjunct matrices to detect q touches. However, a q-separable matrix has $\mathcal{O}(N^q)$ decoding complexity whereas a q-disjunct matrix can be decoded with $\mathcal{O}(MN)$ decoding complexity. Thus, a q-disjunct matrix is more efficient than a q-separable matrix in decoding perspective. Assuming that the rate of energy consumption in analog sensing is higher than that of digital decoding, we use a q-separable matrix to reduce the total energy consumption. Kautz and Singleton propose the *uniquely decipherable code* of order k (UD_k) [6]. UD_2 is to distinguish up to 2 column vectors in a test matrix from a linear measurement, and the minimum number of tests can be $M \sim \left(\lceil (2N)^{2/3} \rceil + 1\right)$ with the change detector. Decoding touch locations with UD_2 is different from the decoding method of single-touch detection. The decoding can be performed with a precomputed lookup table, which requires the memory space of $\sum_{i=1}^{q} \binom{N}{i} = \binom{N}{1} + \binom{N}{2}$. However, without using the lookup table, the decoding is still possible with $\mathcal{O}(N^q)$ computational complexity.

4. ENERGY CONSUMPTION

To compare energy consumption between the standard and the proposed detection method, a self-capacitance touch screen with $N \times 50$ pixels is considered. One of the advanced touch screen controllers requires 2.6 mW power consumption to scan 1.44k pixels per second [7]. The controller consumes 2.6 mW/1.44k $\approx$ 1.81μJ energy per node. Thus, P_{std} = $(1.81 \times 50N) F_{update} \mu$W power is required by the standard method, where F_{update} is the screen update rate. The proposed method consumes P_{GT} = $90.5 F_{update}(\lceil \log_2(N) \rceil + 1)\mu$W total power without the change detector. Moreover, assuming that a touch-input takes place on the touch screen by 10% (R_{touch}) of the total sensing time, we can achieve even more power savings through the proposed detection scheme with the change detector because only one measurement is used to detect the status of a touch input. Therefore, the power consumption will be lowered by P_{GT}^{LOW} = $90.5 F_{update}(R_{touch} \lceil \log_2(N) \rceil + 1)\mu$W. However, extra energy is needed for decoding operations which does not exist in the standard measurement scheme. Today's embedded processors or DSPs show power consumption of 20 MIPS/mW, where MIPS stands for million instructions per second [8]. We compare the power consumptions of the proposed method with the standard method, and the results are summarized in Table 1, 2 assuming F_{update} = 100Hz and R_{touch} = 10%. Using the lookup table, the decoding cost consists of memory cost and processing cost to find the touch locations. We compute the total power consumption when we use UD_2 for detecting up to two-touch locations in Table 2.

5. SIMULATION

Monte Carlo simulations are performed to evaluate the proposed detection scheme using MATLAB. Choosing simulation parameters, typical baseline capacitance is measured between 10 and 300 pF depending on the sensor design and the change of capacitance is shown in the range of 0.1 and 10 pF [9]. In our simulations, we select $c_k = 10$ pF and $s_k = 0.1$ pF. Single-touch location is estimated varying noise variances from 5 to 40 dB SNRs. A 10-bit ADC is chosen to quantize the sensor signals and the ADC shows up to 60 dB SNR after quantization. A touch location is randomly generated on N-sensor nodes. The probability of error is computed by comparing the detection results with the generated ground truth of the touch locations after performing 1,000 tests under various noise conditions. If $N = 8$, the proposed scheme shows an equivalent performance to that of the standard sensing if the SNR is higher than 28 dB in Fig. 3 (a). If $N = 32$, a higher SNR (32 dB) is required to obtain the same performance as shown in Fig. 3 (b). Using current circuit technology, over 30 dB SNR is achievable from typical touch controllers for self-capacitance systems [4].

6. CONCLUSION

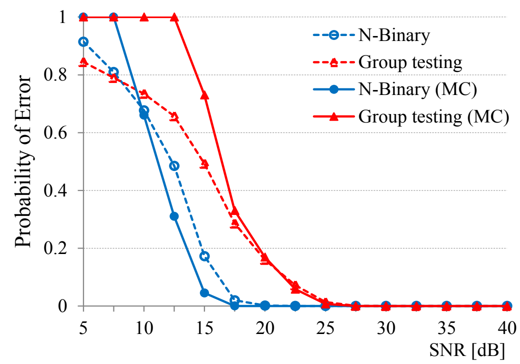
We proposed a new touch detection method that improves sensing latency and energy consumption using the concept of group testing. We compare the detection performances and power consumptions of the proposed method with the standard approach based on multiplexing touch sensors. The proposed method shows equivalent performance to detect a single-touch and two-touch locations with significant energy reduction. To detect more than two-touch locations, a mild noise condition (>30 dB SNR) is required to expand the proposed method. In practice, touch screens suffer from a dynamic change in baseline capacitance depending on an environmental condition and the effect needs to be investigated in the future study.

Table 1. Energy consumption: single-touch

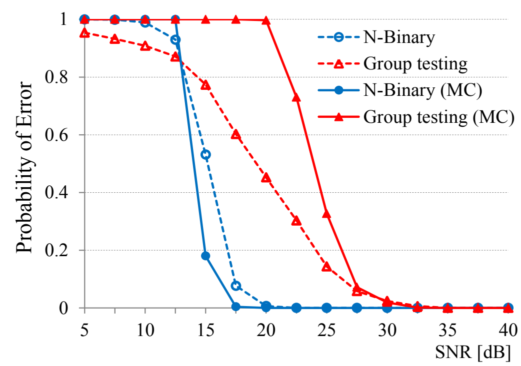
(N, m)	Standard [mW]	Group testing ($q = 1$) [mW]
(8, 4)	72.40	11.77
(16, 5)	144.80	12.67
(32, 6)	289.60	13.58

Table 2. Energy consumption: two-touch

(N, m)	Standard [mW]	Group testing ($1 \leq q \leq 2$) (encode [mW], decode [mW])
(9, 8)	81.45	(16.29, 1.1)
(15,11)	135.75	(19.01, 3.0)
(25,16)	226.25	(23.53, 8.1)



(a) $N = 8$



(b) $N = 32$

Fig. 3. Comparison of the probability of error in single-touch detection if $N = 8$ (a) and $N = 32$ (b). N-Binary denotes the results of N-binary hypothesis testing and Group testing means the results of the proposed low energy scheme. The dashed lines (N-binary and Group testing) show the theoretical performances and the solid lines indicate simulation results.

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