A Highly Linear and Accurate Touch Data Extraction Algorithm Based on Polar Coordinates for Large-Sized Capacitive Touch Screen Panels

Jae-Sung An, *Student Member*, IEEE, Seong-Kwan Hong, *Member*, IEEE, and Oh-Kyong Kwon, *Member*, IEEE

**Abstract — ***In this paper, a polar coordinate-based touch data extraction (PCTDE) algorithm is proposed to enhance the linearity and accuracy of touch coordinates for large-sized capacitive touch screen panels (TSPs) with a wide electrode pitch. The proposed PCTDE algorithm accurately extracts the touch coordinates by calculating the distance and directional angle between the touch point and the intersection of the transmitter and receiver electrodes. In addition, the interference between two touch points in multi-touch is reduced by decreasing the differential rate of touch data so that the exact touch coordinates can be determined. We evaluated the proposed algorithm using a 46-inch TSP with an 8.5 mm electrode pitch. To verify the linearity and accuracy of touch coordinates, the standard deviation of the slope of the touch coordinates and the average distance error are calculated, respectively. In single-touch, the linearity and accuracy of touch coordinates are improved by 56.7 % and 57.8 %, respectively, compared with those using the best previously-reported touch-sensing algorithm. In multi-touch, the linearity and accuracy of touch coordinates are improved by 56.7 % and 64.2 %, respectively*[1].

Index Terms — Touch-sensing algorithm, capacitive touch, multi-touch, touch screen panel.

I. Introduction

Capacitive touch screen panels (TSPs) are widely used in various mobile applications such as smart watches, smart phones, and tablet PCs [1]-[5]. Recently, the use of large-sized capacitive TSPs has gradually grown in commercial applications, such as public displays and electronic white boards, because capacitive TSPs have many advantages including their high sensitivity, durability, and multi-touch capability [6]-[10]. Fig. 1 shows the general touch-sensing system. A digital signal processing (DSP) unit sends the control signal to the excitation circuit. The capacitive TSP takes the excitation signals generated from the excitation circuit and transfers the charge signals to the readout circuit.

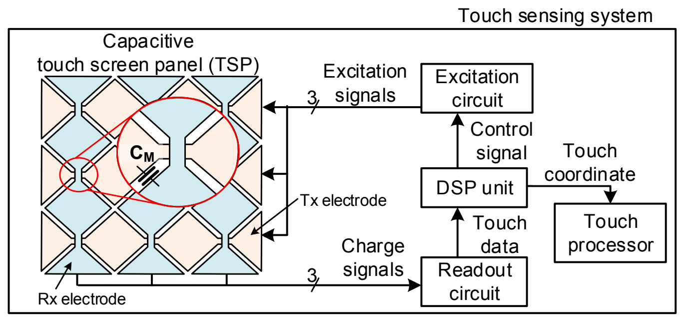

Fig. 1. General touch-sensing system.

The amplitude of the charge signals varies according to the mutual capacitance (C_M) between the transmitter (Tx) and receiver (Rx) electrodes in the TSP. The readout circuit generates touch data and sends it to the DSP unit to calculate the touch coordinates using a touch-sensing algorithm. The calculated touch coordinates are transferred to the touch processor to perform touch operations.

To use the capacitive TSP with a wide electrode pitch in the touch-sensing system, there are several considerations to bear in mind. These include the RC delay of electrodes, influence from external noise including conduction and display noise, and the linearity of the touch coordinates. To minimize the RC delay of electrodes, a metal mesh panel is used instead of an indium tin oxide (ITO) panel because the sheet resistance of the metal mesh panel is much smaller than that of the ITO panel [7]. To reduce the influence of external noise, several noise reduction methods have been investigated in attempts to enhance the signal-to-noise ratio [8]-[10]. Since the electric field absorptivity of a finger between the Tx and Rx electrodes is not proportional to the distance between the finger and the electrodes, variation in C_M between the Tx and Rx electrodes nonlinearly increases according to the position of the finger [11]. Accordingly, as the electrode pitch of the TSP is widened, the nonlinear C_M variation in the TSP worsens. Thus, it is difficult to achieve high linearity and accuracy of the touch coordinates using a wide electrode pitch-based TSP (as compared to a TSP with a narrower pitch). Therefore, a precise touch-sensing algorithm is required to improve the linearity and accuracy of the touch coordinates.

Several touch-sensing algorithms have been researched to determine linear and accurate touch coordinates [11]-[14]. The interpolation algorithm [12] determines the touch coordinates by interpolating a number of touch data. However, when the

[1] Jae-Sung **An is** with the Department of Electrical and Computer Engineering at Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul, 04763, Korea (e-mail: jaesungan@hanyang.ac.kr).

Seong-Kwan Hong is with the Department of Electronic Engineering at Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul, 04763, Korea (e-mail: seongkhong@hanyang.ac.kr).

Oh-Kyong Kwon is with the Department of Electronic Engineering at Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul, 04763, Korea (e-mail: okwon@hanyang.ac.kr).

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TSP has a wide electrode pitch, it is difficult to achieve high linearity and accuracy of the touch coordinates because a number of touch data cannot be obtained from the TSP. The weighted average algorithm [11] easily and rapidly determines the touch coordinates by using weighted touch data, which is obtained by sensing variation in the touch data at a touched electrode and its two adjacent electrodes. However, the linearity and accuracy of touch coordinates are degraded due to nonlinear variation in C_M between the Tx and Rx electrodes.

In this paper, a new touch-sensing algorithm for a TSP with a wide electrode pitch is proposed and implemented in a DSP unit to improve the linearity and accuracy of the touch coordinates. Section II describes the operation of the proposed touch-sensing algorithm. The simulation and experimental results of the PCTDE algorithm are presented and compared with previous works in Sections III and IV, respectively. Finally, conclusions are given in Section V.

II. PROPOSED TOUCH-SENSING ALGORITHM

Fig. 2 shows the proposed polar coordinate-based touch data extraction (PCTDE) algorithm, which consists of a data preprocessing block, a data interference reduction block, and a touch coordinate extraction block. The data processing block receives touch data from the readout circuit and reduces the external noise using a digital low-pass filter; it also compensates for process variation in the TSP. Then, the data interference reduction block minimizes the interference between two touch points in multi-touch. Finally, the touch coordinate extraction block determines linear and accurate touch coordinates by calculating the distance and directional angle between the touch point and the intersection of the Tx and Rx electrodes. The determined touch coordinates are sent to the touch processor and displayed on the display panel.

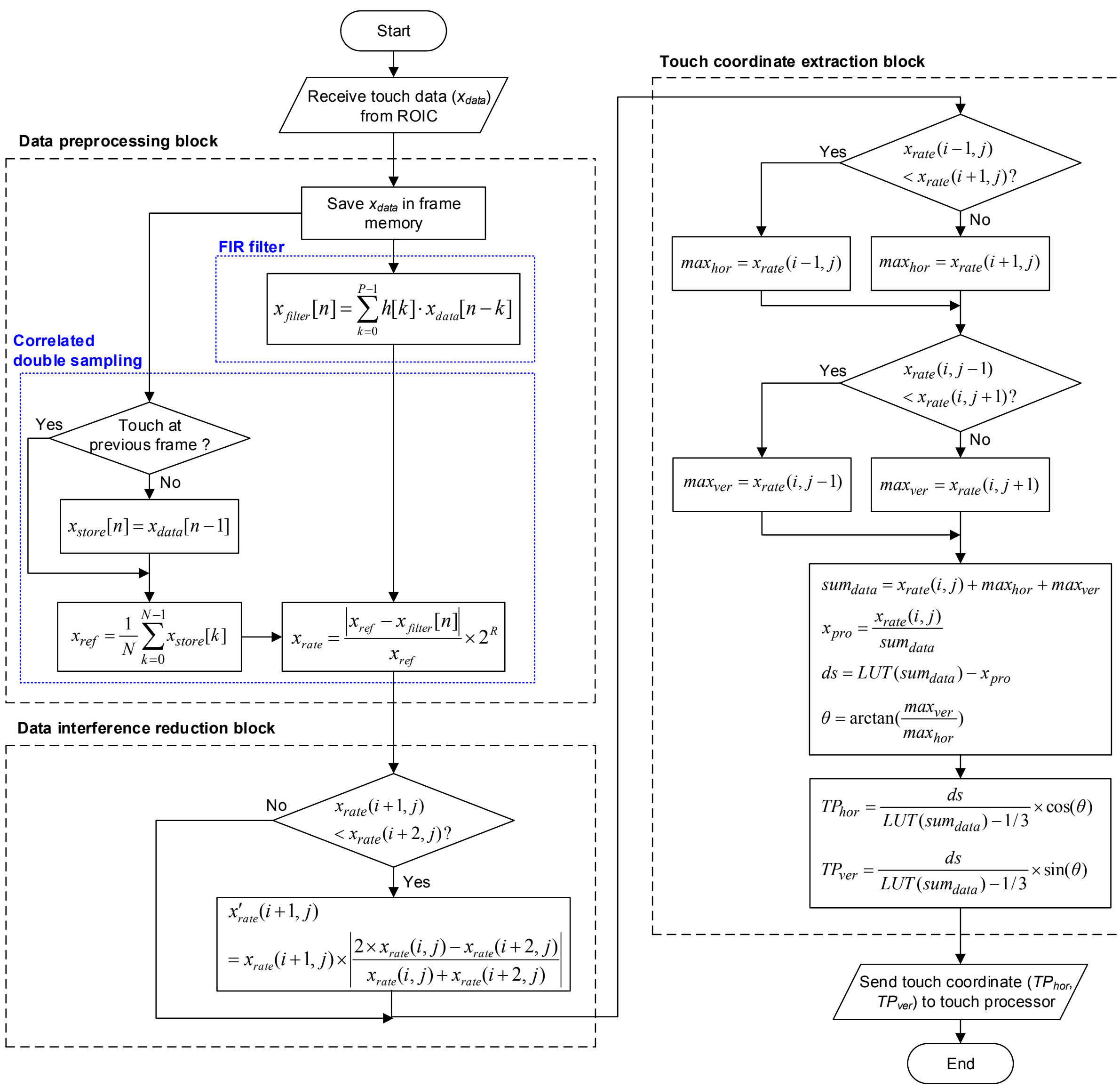


Fig. 2. Proposed polar coordinate-based touch data extraction (PCTDE) algorithm.

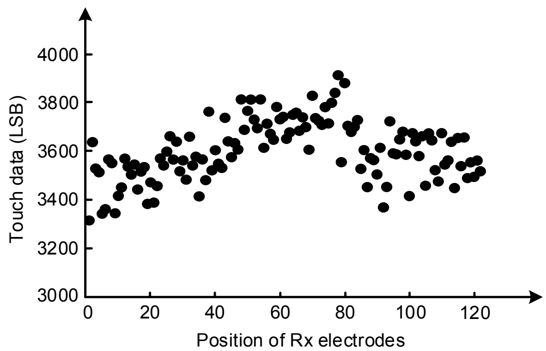


Fig. 3. Touch data according to the position of Rx electrodes in the untouched state.

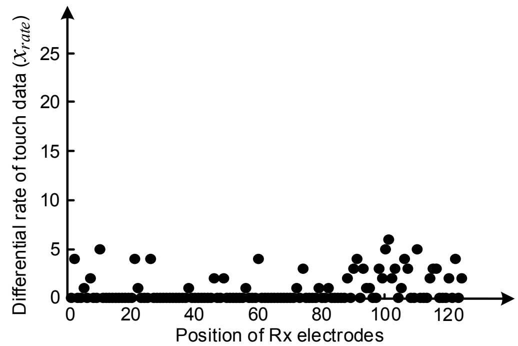


Fig. 4. The x_{rate} according to the position of Rx electrodes in the untouched state using the CDS method.

A. Data Preprocessing Block

In large-sized capacitive TSPs, touch data received from the readout circuit varies considerably according to the position of Rx electrodes in the untouched state, as shown in Fig. 3. This variation is primarily due to process variation in the TSP, electrical characteristic variation of each readout circuit, and non-uniform influences on the capacitive TSP from external noise.

The data preprocessing block reduces external noise at high frequencies by adopting a finite impulse response (FIR) filter. Furthermore, it compensates for process variation in the TSP and reduces external noise at low frequencies by employing the correlated double sampling (CDS) method.

As shown in the data preprocessing block of Fig. 2, the touch data (x_{data}) are received from the readout circuit and saved in the frame memory. Then, the FIR filter [15] reduces external noise at high frequencies according to the following equation:

$$x_{filter}[n] = \sum_{k=0}^{P-1} h[k] \cdot x_{data}[n-k], \tag{1}$$

where $x_{filter}[n]$, P, $h[k]$, and $x_{data}[n\text{-}k]$ are the filtered touch data at the n-th frame, filter order, filter coefficient at the k-th filter order, and touch data at the (n-k)-th frame, respectively. In the PCTDE algorithm, the optimal value of P is experimentally set to 11 since the external noise is no longer reduced when P is greater than 11. The $h[k]$ uses a Hamming window function to easily and accurately filter out external noise.

In the untouched state of the previous frame time, the stored touch data of the current frame time ($x_{store}[n]$) is equal to the touch data of the previous frame time ($x_{data}[n\text{-}1]$). This can be expressed as

$$x_{store}[n] = x_{data}[n-1]. \tag{2}$$

In the touched state of the previous frame time, $x_{store}[n]$ maintains the touch data of the previous frame time. The reference touch data (x_{ref}) is then calculated by averaging x_{store}, which is expressed as

$$x_{ref} = \frac{1}{N}\sum_{k=0}^{N-1} x_{store}[k], \tag{3}$$

where N is the number of reference frame times. Next, the differential rate of touch data (x_{rate}), which represents the degree of C_M variation, is derived using the following CDS equation:

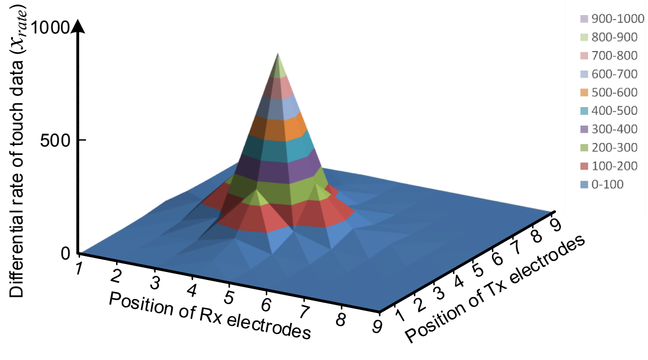
$$x_{rate} = \frac{\left| x_{ref} - x_{filter}[n] \right|}{x_{ref}} \times 2^R, \tag{4}$$

where R is the resolution of the x_{rate}. In this work, R is set to be 12-bit. Fig. 4 shows the x_{rate} according to the position of Rx electrodes in the untouched state, representing that the CDS method compensates for process variation in the TSP and reduces external noise at low frequencies.

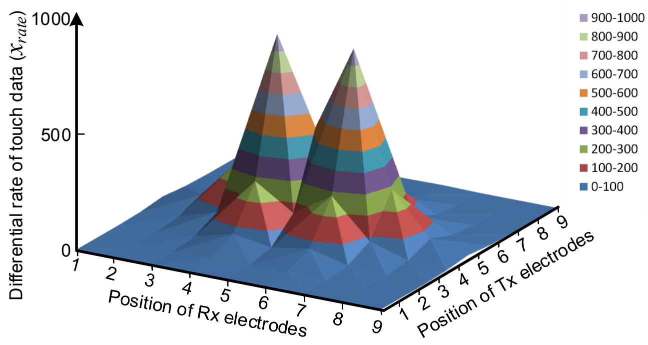
B. Data Interference Reduction Block

The two-dimensional x_{rate} at a single-touch point is distributed according to the position of the Tx and Rx electrodes, as shown in Fig. 5 (a). When two touch points are closely located, as shown in Fig. 5 (b), the x_{rate} between two touch points increases due to interference between the touch points. Thus, it is difficult to determine the exact touch coordinates.

In the data interference reduction block, the x_{rate} between two touch points is compared with that of their adjacent Tx and Rx electrodes. When the x_{rate} between two touch points is similar to that of their adjacent Tx and Rx electrodes, it is considered that interference between two touch points does not occur. On the other hand, when the x_{rate} between two touch points is greater than that of their adjacent Tx and Rx electrodes, it is considered that interference between two touch points occurs. Since the x_{rate} between two touch points is proportionally reduced by the difference in the x_{rate} of their adjacent electrodes, the interference between two touch points can be reduced according to the following equation:



(a)



(b)

Fig. 5. Distribution of the x_{rate} at (a) a single-touch point and (b) multi-touch points.

$$x'_{rate}(i+1,j) = x_{rate}(i+1,j) \times \left| \frac{2 \times x_{rate}(i,j) - x_{rate}(i+2,j)}{x_{rate}(i,j) + x_{rate}(i+2,j)} \right|, \qquad (5)$$

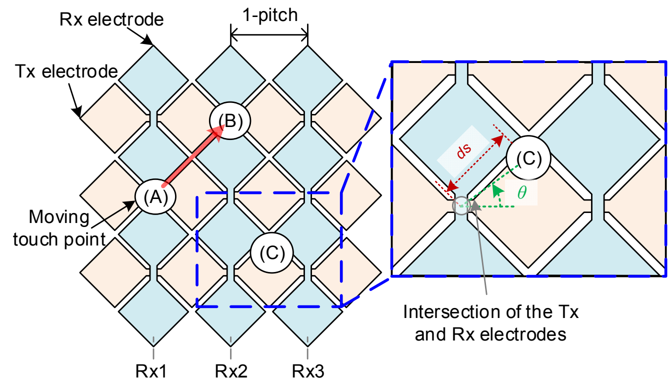
where i and j represent the positions of the Rx and Tx electrodes, respectively. Equation (5) can be applied in all directions of the TSP since the TSP has a symmetric structure.

C. Touch Coordinate Extraction Block

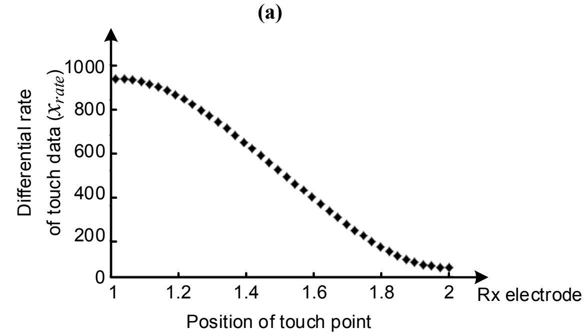
When the touch point diagonally moves from one intersection (A) of the Tx and Rx electrodes to the next intersection (B), as shown in Fig. 6(a), the x_{rate} varies nonlinearly according to the position of the touch point (Fig. 6(b)), and thereby it is difficult to determine the exact touch coordinates.

To extract linear and accurate touch coordinates, the touch coordinate extraction block uses the distance (ds) and directional angle (θ) between the touch point (C) and the intersection of the Tx and Rx electrodes, as depicted in the enlarged view of Fig. 6(b). The ds is calculated using the following equations:

$$max_{hor} = \begin{cases} x_{rate}(i-1,j), & if \quad x_{rate}(i-1,j) < x_{rate}(i+1,j) \\ x_{rate}(i+1,j), & else \end{cases}, \qquad (6)$$



(a)



(b)

Fig. 6. (a) Touch point movement and enlarged view of electrodes and (b) the x_{rate} according to the position of the touch point.

$$max_{ver} = \begin{cases} x_{rate}(i,j-1), & if \quad x_{rate}(i,j-1) < x_{rate}(i,j+1) \\ x_{rate}(i,j+1), & else \end{cases}, \qquad (7)$$

$$sum_{data} = x_{rate}(i,j) + max_{hor} + max_{ver}, \qquad (8)$$

$$x_{pro} = \frac{x_{rate}(i,j)}{sum_{data}}, \qquad (9)$$

$$ds = LUT(sum_{data}) - x_{pro}, \qquad (10)$$

where max_{hor}, max_{ver}, sum_{data}, $x_{pro.}$, and $LUT(sum_{data})$ are the maximum x_{rate} in the horizontal electrodes; maximum x_{rate} in the vertical electrodes; sum of the touch data, which varies according to the diameter of the touch point; proportion of the x_{rate}; and maximum x_{pro} according to the sum_{data}, whose values are stored in a look-up-table (LUT), respectively. $LUT(sum_{data})$ is used to compensate for the variation in C_M according to the diameter of the touch point. The θ is then calculated using the following equation:

$$\theta = \arctan\left(\frac{max_{ver}}{max_{hor}}\right). \qquad (11)$$

The horizontal and vertical touch coordinates (TP_{hor}, TP_{ver}) can be extracted by calculating the following equations:

$$TP_{hor} = \frac{ds}{LUT(sum_{data}) - 1/3} \times \cos(\theta), \qquad (12)$$

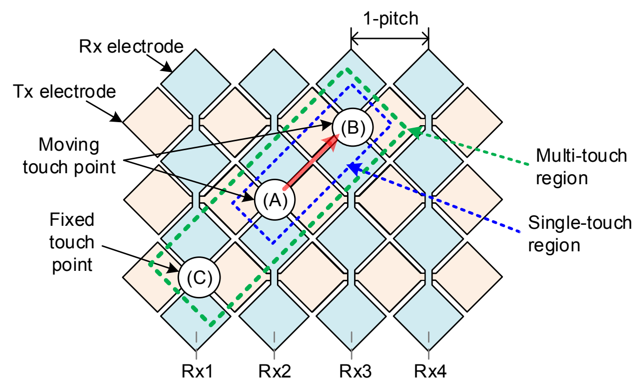


Fig. 7. The diagonal movements of touch points in single- and multi-touch.

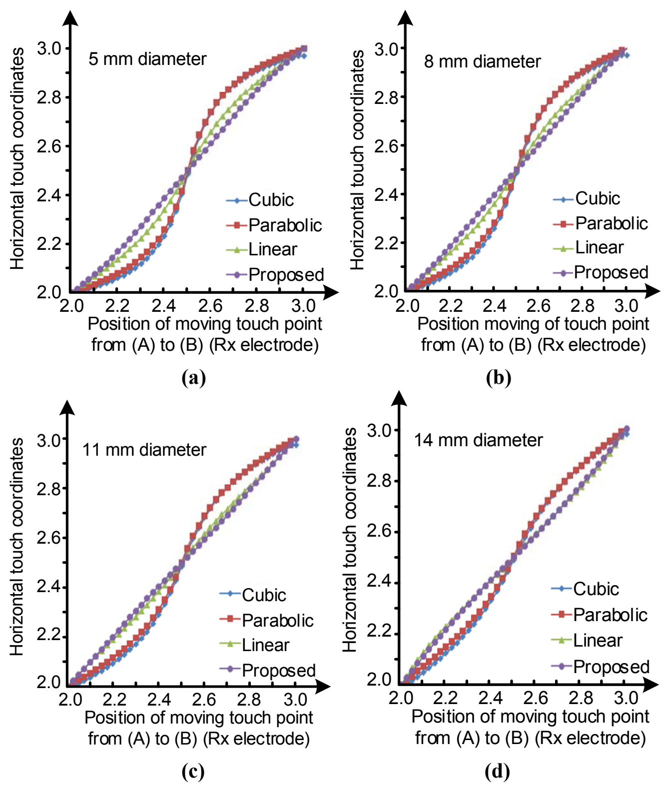


Fig. 8. The horizontal touch coordinates according to the position of a touch point with diameters of (a) 5 mm, (b) 8 mm, (c) 11 mm, and (d) 14 mm in single-touch.

$$TP_{ver} = \frac{ds}{LUT\,(sum_{data}) - 1/3} \times \sin(\theta). \tag{13}$$

All trigonometric functions are implemented using the *LUT* to reduce the complexity of the calculation.

III. Simulation Results

To verify the performance of the PCTDE algorithm, a capacitive TSP with a diamond pattern, which has an electrode pitch of 8.5 mm, is used. In addition, a metal mesh panel instead of an ITO panel is used to reduce the RC delay because the sheet resistance of a metal mesh panel (0.05 Ω/□) is much smaller than that of an ITO panel (150-300 Ω/□).

TABLE I
Comparison of the Standard Deviation of the Slope of Touch Coordinates (SDSTC)

Diameter of touch point	Parabolic algorithm [11]	Linear algorithm [11]	Cubic interpolation algorithm [12]	Proposed algorithm
5 mm	0.813	0.360	0.882	0.149
8 mm	0.678	0.237	0.745	0.085
11 mm	0.511	0.099	0.585	0.043
14 mm	0.327	0.144	0.411	0.085

Fig. 7 shows the diagonal movements of touch points that was used to verify the linearity and accuracy of touch coordinates in single- and multi-touch.

In single-touch, a touch point diagonally moves from one intersection (A) of the Tx and Rx electrodes to the next intersection (B). Fig. 8 shows the TP_{hor} according to the position of the touch point with touch diameters of 5 mm, 8 mm, 11 mm, and 14 mm. The TP_{ver} is exactly equal to the TP_{hor} because the TSP has a symmetric structure. The performance of the proposed PCTDE algorithm is compared with that of parabolic, linear [11], and cubic interpolation [12] algorithms. To verify the linearity, the standard deviation of the slope of touch coordinates (*SDSTC*) is used. This is expressed as

$$SDSTC = \sqrt{\frac{1}{M} \times \sum_{k=1}^{M} \left(slope_{hor}(k) - \overline{slope_{hor}} \right)^2}, \tag{14}$$

$$slope_{hor}(k) = \frac{TP_{hor}(k+1) - TP_{hor}(k)}{IP_{hor}(k+1) - IP_{hor}(k)}, \tag{15}$$

where $slope_{hor}$ is the slope of touch coordinates in the horizontal direction, M is the number of touch points, and $IP_{hor}(k)$ is the k-th input position of the touch point in the horizontal direction. As summarized in Table I, the average *SDSTCs* of the parabolic, linear, cubic interpolation, and proposed algorithms are 0.656, 0.582, 0.210, and 0.091, respectively. As a result, the average *SDSTC* of the proposed algorithm is 56.7 % less than that of the best previously-reported algorithm. This indicates that the PCTDE algorithm provides better touch linearity in single-touch than other algorithms for touch points with various diameters.

The accuracy in single-touch is verified using the extracted touch coordinates in Fig. 8. To compare the accuracy of the proposed PCTDE algorithm with that of the parabolic, linear, and cubic interpolation algorithms, the average distance error (*ADE*) is used. This is expressed as

$$ADE = \frac{1}{M} \times \sum_{k=1}^{M} \left(\sqrt{\left(TP_{hor}(k) - IP_{hor}(k)\right)^2 + \left(TP_{ver}(k) - IP_{ver}(k)\right)^2} \right), \tag{16}$$

where $IP_{ver}(k)$ is the k-th input position of the touch point in the vertical direction.

TABLE II
COMPARISON OF AVERAGE DISTANCE ERROR (ADE) IN SINGLE-TOUCH

Diameter of touch point	Parabolic algorithm [11]	Linear algorithm [11]	Cubic interpolation algorithm [12]	Proposed algorithm
5 mm	0.145	0.069	0.171	0.028
8 mm	0.123	0.045	0.151	0.013
11 mm	0.094	0.013	0.122	0.005
14 mm	0.056	0.025	0.088	0.016

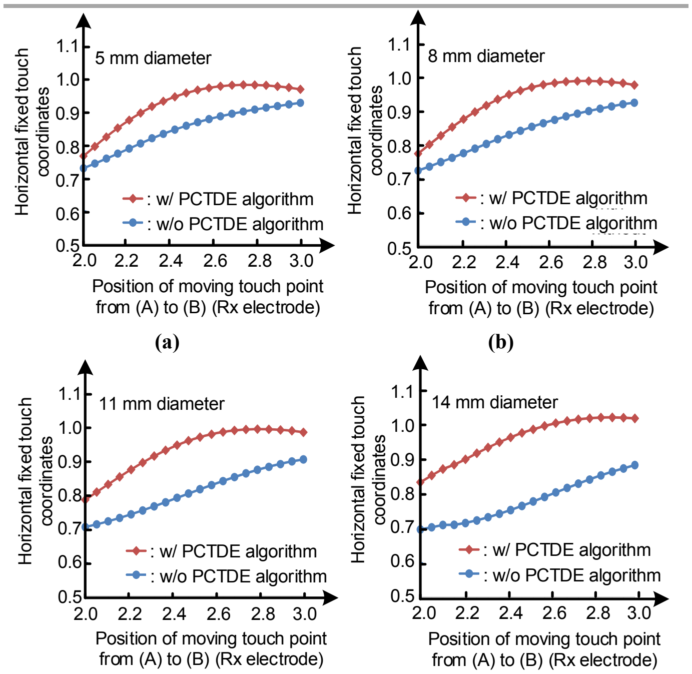


Fig. 9. The horizontal touch coordinates of a fixed touch point with and without the proposed PCTDE algorithm when the touch point moves. Touch point diameters of (a) 5 mm, (b) 8 mm, (c) 11 mm, and (d) 14 mm in multi-touch.

As summarized in Table II, the average *ADEs* of the linear, cubic interpolation, and proposed algorithms in single-touch are 0.105, 0.038, 0.133, and 0.016, respectively. As a result, in single-touch, the average *ADE* of the proposed algorithm is 57.8 % less than that of the best previously-reported algorithm. This indicates that the proposed algorithm dramatically improves the accuracy of touch coordinates relative to other algorithms.

In multi-touch, as shown in Fig. 7, a touch point is diagonally moved from (A) to (B) while a touch point (C) is fixed. Since the SDSTCs in single- and multi-touch are derived from the touch coordinates at the same touch positions, (i.e., (A) and (B)), the linearity of touch coordinates in multi-touch is the same as it is in single-touch.

The accuracy in multi-touch is calculated using the extracted touch coordinates at a touch point (C) since the C_M variation at a touch point (C) is influenced when a touch point moves from (A) to (B). Fig. 9 shows the simulated TP_{hor} of a fixed touch point (C) with and without the proposed PCTDE algorithm as a touch point moves from (A) to (B). This is done with touch point diameters of 5 mm, 8 mm 11 mm, and 14 mm. Table III summarizes the *ADEs* with and without using the PCTDE algorithm in multi-touch. The average *ADE* using the proposed algorithm (0.092) is 64.2 % less than that without using the proposed algorithm (0.257).

TABLE III
COMPARISON OF AVERAGE DISTANCE ERROR (ADE) IN MULTI-TOUCH

Diameter of touch point	With multi-touch algorithm	Without multi-touch algorithm
5 mm	0.103	0.213
8 mm	0.098	0.230
11 mm	0.092	0.271
14 mm	0.076	0.313

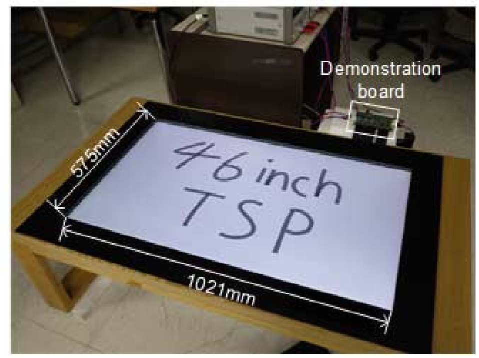


Fig. 10. Demonstration of the proposed PCTDE algorithm.

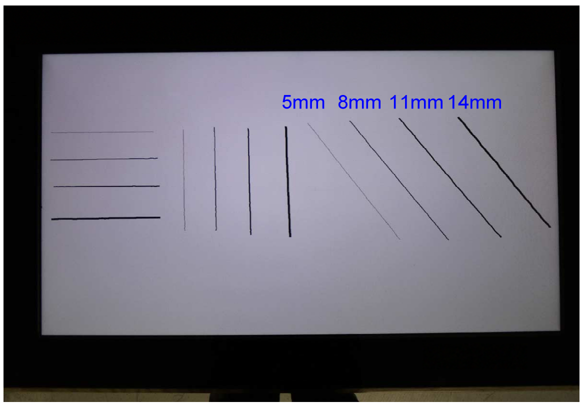
As a result, the linearity and accuracy of touch coordinates in single-touch are improved by 56.7 % and 57.8 %, respectively, compared with those using the best previously-reported touch-sensing algorithm. In multi-touch, the linearity and accuracy of touch coordinates are improved by 56.7 % and 64.2 %, respectively.

IV. EXPERIMENTAL RESULTS

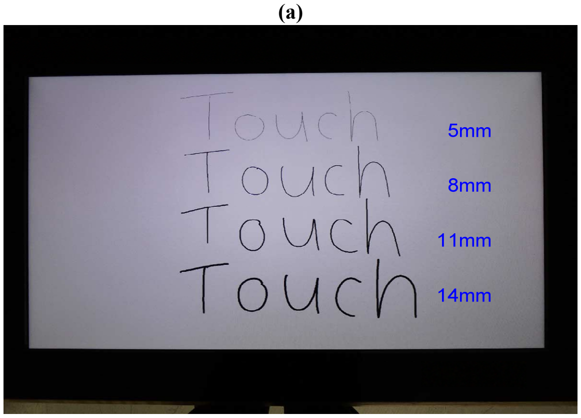
The proposed PCTDE algorithm is experimented using a field-programmable gate array and was successfully demonstrated on a 46-inch capacitive TSP with a resolution of 70 × 120 at a frame frequency of 120 Hz, as shown in Fig. 10. Figs. 11 (a) and (b) show the experimental results of the PCTDE algorithm using lines and words, respectively, with touch point diameters of 5 mm, 8 mm, 11 mm, and 14 mm. These results indicate that the proposed algorithm achieves good linearity and accuracy for touch points with various diameters. Fig. 11 (c) shows the experimental results in multi-touch, which proves that the proposed algorithm works properly. Figs. 12 (a) and (b) demonstrate the experimental results of the linear [11] and proposed PCTDE algorithms, respectively, for different touch point diameters of 3 mm, 5 mm, 8 mm, 11 mm, and 14 mm. The deviations of diagonal lines using the linear and PCTDE algorithms are 2.3 mm and 1.1 mm, respectively. This comparison demonstrates that the diagonal lines made using the proposed algorithm are more linear than those made using the linear algorithm.

V. CONCLUSION

In this paper, we propose a highly linear and accurate touch-sensing algorithm in a touch-sensing system. To improve the linearity and accuracy of touch coordinates in a wide electrode pitch-based capacitive TSP, touch coordinates are precisely determined by calculating the distance and directional angle between the touch point and the intersection of the Tx and Rx electrodes. In addition, the accuracy of the proposed PCTDE algorithm in multi-touch is improved by reducing the interference between two touch points. The proposed algorithm is demonstrated using a 46-inch TSP, which has an 8.5 mm electrode pitch. The linearity and accuracy of touch coordinates in single- and multi-touch are verified by calculating the *SDSTC* and the *ADE*, respectively. In single-touch, the linearity and accuracy of touch coordinates are improved by 56.7 % and 57.8 %, respectively, compared with those using the best previously-reported touch-sensing algorithm. In multi-touch, the linearity and accuracy of touch coordinates are improved by 56.7 % and 64.2 %, respectively. Therefore, the proposed PCTDE algorithm achieves better linearity and accuracy than other algorithms; it provides the best solution for large-sized capacitive TSPs.



(a)



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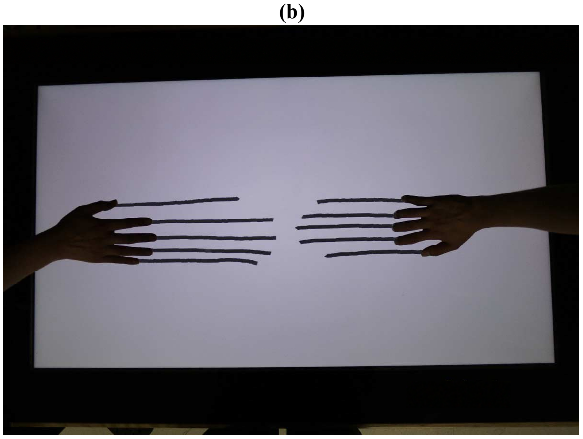
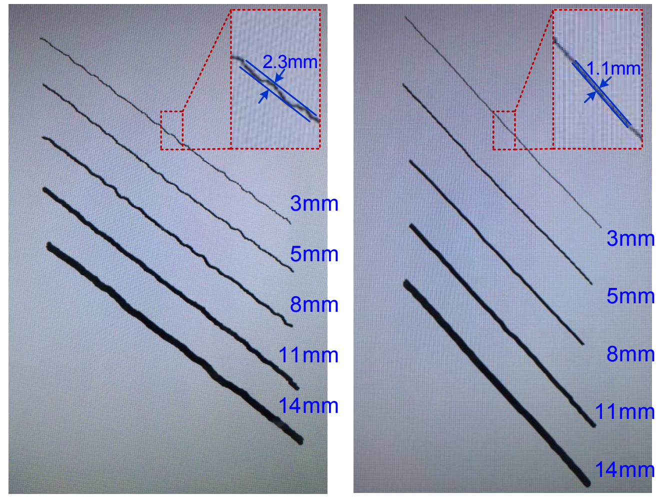


(c)

Fig. 11. Experimental results of the proposed PCTDE algorithm: (a) line, (b) word, and (c) multi-touch.



(a) (b)

Fig. 12. Experimental results of (a) linear [11] and (b) proposed PCTDE algorithms.

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BIOGRAPHIES

Jae-Sung An (S'11) received a B.S. degree in media communications engineering from Hanyang University in Seoul, Korea in 2010. He is pursuing his PhD degree at the same university. His research interests include sensing methodologies, high-precision analog, and mixed signal circuits for capacitive touch screen panel systems.

Seong-Kwan Hong **(M'13) received his PhD degree in electrical engineering from the Georgia Institute of Technology, Atlanta, GA, USA, in 1994.**
He is currently a research professor at Hanyang University, Seoul, Korea.

Oh-Kyong Kwon (S'83 M'88) received his PhD degree in electrical engineering from Stanford University, Stanford, CA, USA, in 1988.
He is currently a professor with the Department of Electronic Engineering at Hanyang University, Seoul, Korea.