Calibration in touch-screen systems

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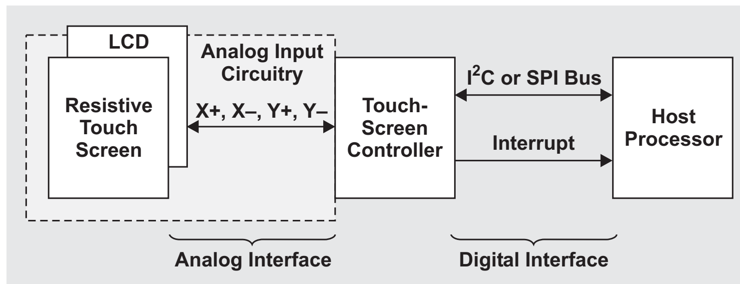
Introduction

Today, more and more different fields are adopting touch screens or touch panels for applications with human/machinery or human/computer interfaces. Figure 1 is a block diagram of a touch-screen system where the touch screen sensor lies on top of the system's display, in this case an LCD panel.

The touch-screen controller in Figure 1 does not need any calibration by itself. However, products or instrumentation equipped with a touch screen normally require a calibration routine upon power up because it is difficult to perfectly align a touch screen's coordinates with those of the display underneath it. Calibration is necessary when the coordinates of the area touched on the screen are not sufficiently close to the coordinates on the display. Without proper calibration, software may not respond correctly when a soft button or icon is pressed.

This article presents concepts and methods for the calibration of touch-screen systems. Software-programming algorithms and their implementation are also discussed.

Figure 1. Typical four-wire resistive touch-screen system



Touch-coordinate errors

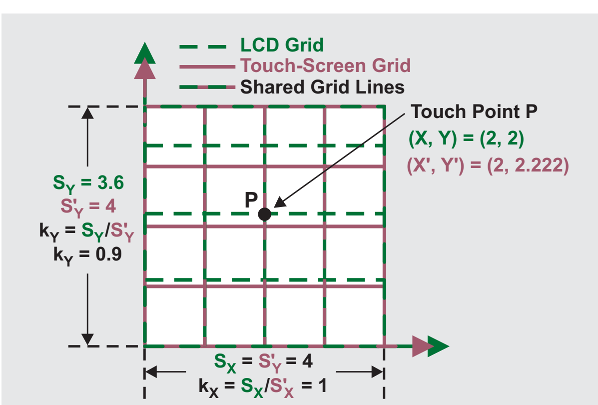
When pressure is applied to the touch screen, the touch-screen controller senses it and takes a measurement of the X and Y coordinates. Several sources of error can affect the accuracy and reliability of this measurement. The majority of these errors can be attributed to electrical noise, scaling factors, and mechanical misalignments.

Electrical noise comes from the display and backlight, the human interface, the panel surface's vibration, and the electrostatic discharge and electromagnetic pulses caused by users and their environments. This article does not address noise issues. For more information on handling noise, please see Reference 1.

Scaling factors and mechanical misalignments originate in the parts and assembly of the touch screen and the display. Typically, the touch-screen controller and display in a system do not have the same resolution, so scaling factors are needed to match their coordinates to each other. For example, consider a touch-screen system that uses an LCD with a resolution of 1024 (X coordinate) × 768 (Y coordinate) and the Texas Instruments TSC2005 touch-screen controller with 12-bit (4096 × 4096) resolution. The scaling factors to match them are $k_X = S_X/S'_X = 1024/4096 = 0.25$ for the X-axis coordinate and $k_Y = S_Y/S'_Y = 768/4096 = 0.1875$ for the Y-axis coordinate, where S_X is the LCD's X-axis resolution, S'_X is the touch-screen controller's X-axis resolution, S_Y is the LCD's Y-axis resolution, and S'_Y is the touch-screen controller's Y-axis resolution. Thus, a touch-screen controller's X coordinate, X′, should be understood by the LCD (the host) as $X = k_X \times X'$; and a touch-screen controller's Y coordinate, Y′, should be understood by the LCD (the host) as $Y = k_Y \times Y'$.

In the preceding example, k_X and k_Y are simple linear scaling factors based on the resolution specifications for the display and touch-screen controller. "Real-world" scaling factors may vary from part to part and may need to be calibrated to reduce or eliminate any mismatch. An example is shown in Figure 2, where the X-axis scale is the same on the LCD and the touch screen, or $k_X = S_X/S'_X = 1$; but the Y-axis scale on the LCD is larger than that on the touch screen, with the scaling factor of $k_Y = S_Y/S'_Y = 3.6/4 = 0.9$. Thus, a point P (X′, Y′) = (2, 2.222) on the touch screen should be scaled to (X, Y) = (2, 2) for the LCD (the host).

Figure 2. Scaling factors on the Y axes of LCD and touch screen



Mechanical misalignment between the display and the touch screen includes moving and rotation errors, as shown in Figure 3. Figure 3a shows the relative position shifts of ΔX in the X direction and ΔY in the Y direction; and Figure 3b shows the relative rotation, Δθ, between the LCD and the touch screen.

Consider a point P, read as (X′, Y′) on the touch screen. The display should read a moving error like that shown in Figure 3a as (X′ + ΔX, Y′ + ΔY). For a rotation error like that shown in Figure 3b, the point on the touch screen is (R × cosθ, R × sinθ), or on the display is [R × cos(θ–Δθ), R × sin(θ–Δθ)], where R is the distance from origin C, or (0, 0), to the point P.

Mathematical expression

Calibration of the touch screen translates the coordinates reported by the touch-screen controller into coordinates that accurately represent the point and image location on the display or LCD. The result of calibration is a set of scaling factors that allow correction of the moving and rotation errors that are due to mechanical misalignments.

Consider the point P, represented as (X, Y) on the display and (X′, Y′) on the touch panel. Counting in the scaling factor in Figure 2 and the moving and rotation errors in Figure 3, the touch-screen coordinate X can be expressed as

$$\begin{aligned} X &= k_X \times R \times \cos(\theta - \Delta\theta) + \Delta X \\ &= k_X \times R \times \cos\theta \times \cos(\Delta\theta) + k_X \times R \times \sin\theta \times \sin(\Delta\theta) + \Delta X \\ &= k_X \times X' \times \cos(\Delta\theta) + k_X \times Y' \times \sin(\Delta\theta) + \Delta X \qquad \textbf{(1)} \\ &= \alpha_X \times X' + \beta_X \times Y' + \Delta X, \end{aligned}$$

where X′ = R × cosθ, Y′ = R × sinθ, $\alpha_X = k_X \times \cos(\Delta\theta)$, and $\beta_X = k_X \times \sin(\Delta\theta)$. Similarly, the touch-screen coordinate Y can be expressed as

$$\begin{aligned} Y &= k_Y \times R \times \sin(\theta - \Delta\theta) + \Delta Y \\ &= k_Y \times R \times \sin\theta \times \cos(\Delta\theta) - k_Y \times R \times \cos\theta \times \sin(\Delta\theta) + \Delta Y \\ &= k_Y \times Y' \times \cos(\Delta\theta) - k_Y \times X' \times \sin(\Delta\theta) + \Delta Y \qquad \textbf{(2)} \\ &= \alpha_Y \times X' + \beta_Y \times Y' + \Delta Y, \end{aligned}$$

where $\alpha_Y = -k_Y \times \sin(\Delta\theta)$, and $\beta_Y = k_Y \times \cos(\Delta\theta)$.

From Equations 1 and 2 it is obvious that, to get the coefficients α_X, α_Y, β_X, β_Y, ΔX, and ΔY, at least three independent points are needed. The points are independent if they are not on one linear line (see Figure 4). Assuming that (X_1, Y_1), (X_2, Y_2), and (X_3, Y_3) are three independent

Figure 3. Mechanical misalignments

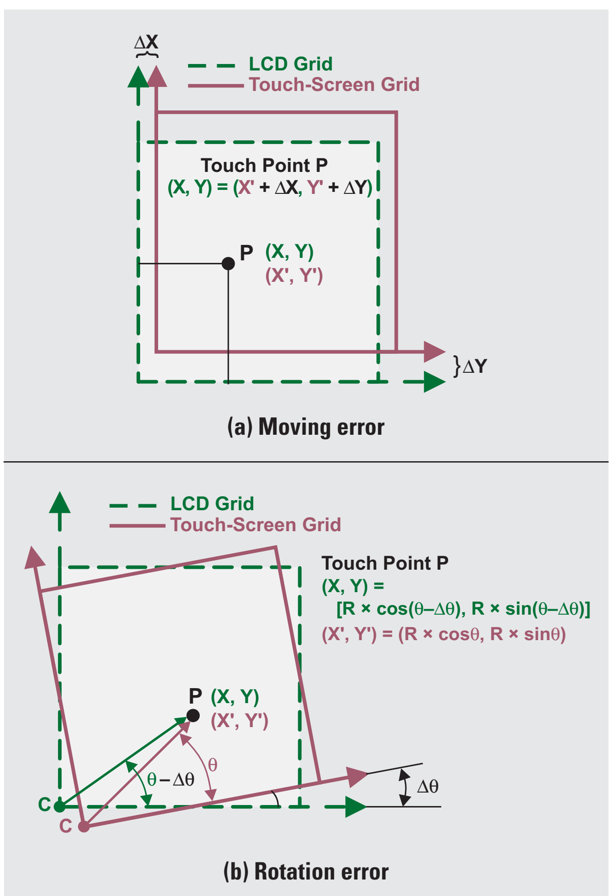
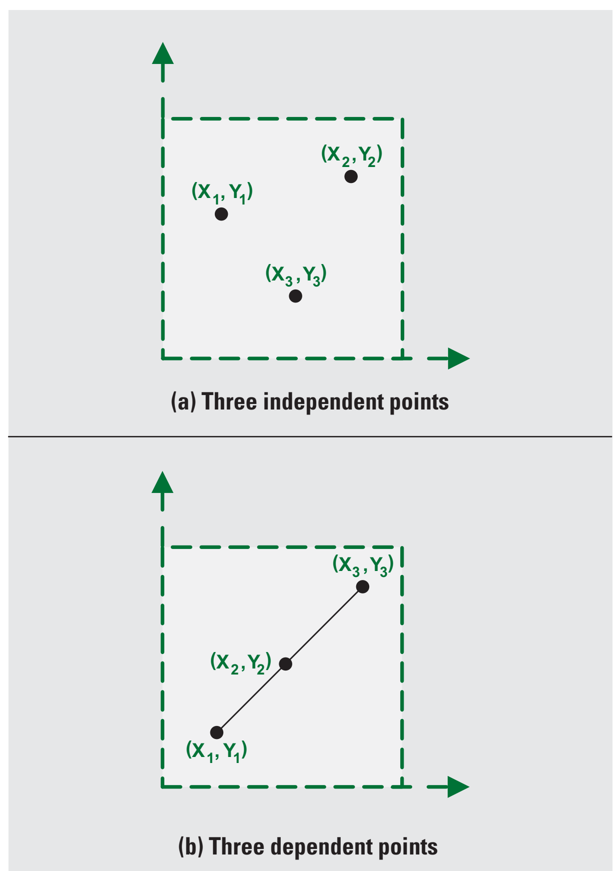


Figure 4. Independent (not on one linear line) and dependent points



points selected on the LCD, and (X'_1, Y'_1), (X'_2, Y'_2), and (X'_3, Y'_3) are the corresponding points on the touch screen, Equations 1 and 2 can be used to write Equation 3:

$$\begin{aligned} X_1 &= \alpha_X \times X'_1 + \beta_X \times Y'_1 + \Delta X \\ X_2 &= \alpha_X \times X'_2 + \beta_X \times Y'_2 + \Delta X \\ X_3 &= \alpha_X \times X'_3 + \beta_X \times Y'_3 + \Delta X \end{aligned} \tag{3}$$

$$\begin{aligned} Y_1 &= \alpha_Y \times X'_1 + \beta_Y \times Y'_1 + \Delta Y \\ Y_2 &= \alpha_Y \times X'_2 + \beta_Y \times Y'_2 + \Delta Y \\ Y_3 &= \alpha_Y \times X'_3 + \beta_Y \times Y'_3 + \Delta Y \end{aligned}$$

Equation 3 can be rewritten in matrix form:

$$\begin{pmatrix} X_1 \\ X_2 \\ X_3 \end{pmatrix} = A \times \begin{pmatrix} \alpha_X \\ \beta_X \\ \Delta X \end{pmatrix} \text{ and } \begin{pmatrix} Y_1 \\ Y_2 \\ Y_3 \end{pmatrix} = A \times \begin{pmatrix} \alpha_Y \\ \beta_Y \\ \Delta Y \end{pmatrix}, \tag{4}$$

where

$$A = \begin{pmatrix} X'_1 & Y'_1 & 1 \\ X'_2 & Y'_2 & 1 \\ X'_3 & Y'_3 & 1 \end{pmatrix}.$$

Calibration methods

The three independent calibration points shown in Equation 4 should be sufficient to get the scaling factors required to correct the mechanical misalignment between the touch screen and the system display.

To resolve Equation 4, both sides can be multiplied by the inverse of matrix A to get

$$\begin{pmatrix} \alpha_X \\ \beta_X \\ \Delta X \end{pmatrix} = A^{-1} \times \begin{pmatrix} X_1 \\ X_2 \\ X_3 \end{pmatrix} \text{ and } \begin{pmatrix} \alpha_Y \\ \beta_Y \\ \Delta Y \end{pmatrix} = A^{-1} \times \begin{pmatrix} Y_1 \\ Y_2 \\ Y_3 \end{pmatrix}, \tag{5}$$

where A^{-1} is the inverse of matrix A. The three points—(X_1, Y_1), (X_2, Y_2), and (X_3, Y_3)—are designed/selected on the display surface; and the elements in matrix A are measured from the touch screen during calibration.

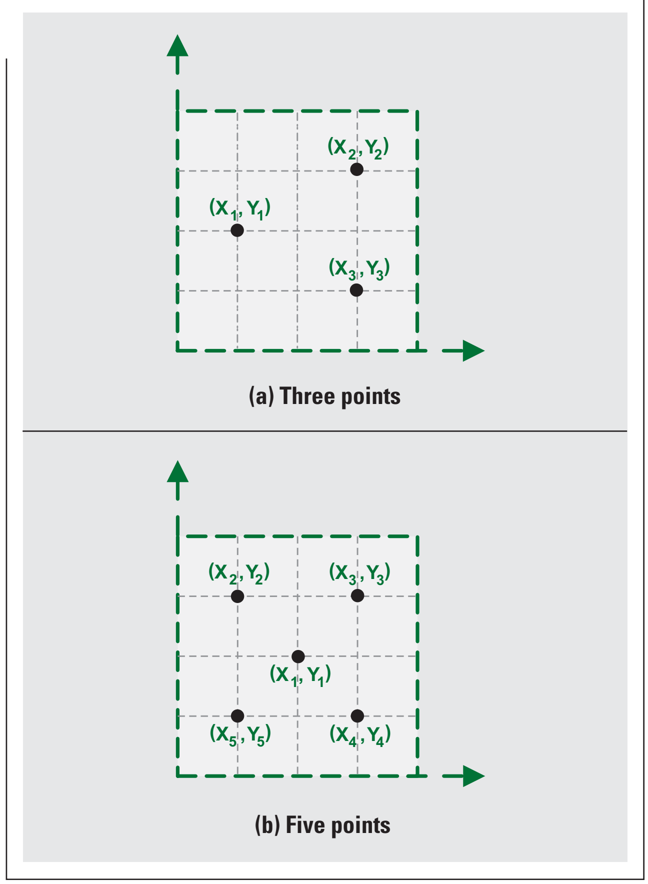
Example 1: Three-point calibration

On a display with 256 × 768 resolution, three calibration points are chosen: (64, 384), (192, 192), and (192, 576). Refer to Figure 5a. During calibration, the three points (678, 2169), (2807, 1327), and (2629, 3367) are measured from a touch panel with 12-bit or 4096 × 4096 resolution. Equation 4 can then be populated with these known values.

$$\begin{pmatrix} X_1 \\ X_2 \\ X_3 \end{pmatrix} = \begin{pmatrix} 64 \\ 192 \\ 192 \end{pmatrix} \qquad \begin{pmatrix} Y_1 \\ Y_2 \\ Y_3 \end{pmatrix} = \begin{pmatrix} 384 \\ 192 \\ 576 \end{pmatrix}$$

$$A = \begin{pmatrix} 678 & 2169 & 1 \\ 2807 & 1327 & 1 \\ 2629 & 3367 & 1 \end{pmatrix}$$

Figure 5. Examples for selecting calibration points



Applying Equation 5 results in $\alpha_X = 0.0623$, $\beta_X = 0.0054$, $\Delta X = 9.9951$, $\alpha_Y = -0.0163$, $\beta_Y = 0.1868$, and $\Delta Y = -10.1458$. Thus the equation for X, from Equation 1, is

$$X = 0.0623 \times X' + 0.0054 \times Y' + 9.9951;$$

and the equation for Y, from Equation 2, is

$$Y = -0.0163 \times X' + 0.1868 \times Y' - 10.1458.$$

In many applications, users may use more than three points in their calibration routines to average or filter the noisy readings from the touch-screen controller. For calibration with $n > 3$,

$$\begin{pmatrix} X_1 \\ X_2 \\ \vdots \\ X_n \end{pmatrix} = A \times \begin{pmatrix} \alpha_X \\ \beta_X \\ \Delta X \end{pmatrix} \text{ and } \begin{pmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_n \end{pmatrix} = A \times \begin{pmatrix} \alpha_Y \\ \beta_Y \\ \Delta Y \end{pmatrix}, \tag{6}$$

where A is an $n \times 3$ matrix with $n > 3$ and rank $(A) = 3$, or

$$A = \begin{pmatrix} X'_1 & Y'_1 & 1 \\ X'_2 & Y'_2 & 1 \\ \vdots & \vdots & \vdots \\ X'_n & Y'_n & 1 \end{pmatrix}.$$

To resolve Equation 6, both sides can be multiplied by A's pseudo-inverse matrix, $(A^T \times A)^{-1} \times A^T$, where A^T is A's transpose matrix. That is, the unknown variables α_X, β_X, ΔX, α_Y, β_Y, and ΔY are resolved from

$$\begin{pmatrix}\alpha_X\\ \beta_X\\ \Delta X\end{pmatrix} = \left(A^T \times A\right)^{-1} \times A^T \times \begin{pmatrix}X_1\\ X_2\\ X_3\end{pmatrix} \text{ and}$$

$$\begin{pmatrix}\alpha_Y\\ \beta_Y\\ \Delta Y\end{pmatrix} = \left(A^T \times A\right)^{-1} \times A^T \times \begin{pmatrix}Y_1\\ Y_2\\ Y_3\end{pmatrix}. \tag{7}$$

The solution of Equation 7 is the least-square-error estimation[2] of these unknown variables.

Example 2: Five-point calibration

The same system as in Example 1 is used, but five calibration points on the display are chosen: (128, 384), (64, 192), (192, 192), (192, 576), and (64, 576). Refer to Figure 5b. Equation 6 can then be populated with the five points measured from the touch panel: (1698, 2258), (767, 1149), (2807, 1327), (2629, 3367), and (588, 3189).

$$\begin{pmatrix}X_1\\ X_2\\ X_3\\ X_4\\ X_5\end{pmatrix} = \begin{pmatrix}128\\ 64\\ 192\\ 192\\ 64\end{pmatrix} \qquad \begin{pmatrix}Y_1\\ Y_2\\ Y_3\\ Y_4\\ Y_5\end{pmatrix} = \begin{pmatrix}384\\ 192\\ 192\\ 576\\ 576\end{pmatrix}$$

$$A = \begin{pmatrix}1698 & 2258 & 1\\ 767 & 1149 & 1\\ 2807 & 1327 & 1\\ 2629 & 3367 & 1\\ 588 & 3189 & 1\end{pmatrix}$$

Using Equation 7 provides a solution similar to that found in Example 1:

$$X = 0.0623 \times X' + 0.0054 \times Y' + 10.0043, \text{ and}$$

$$Y = -0.0163 \times X' + 0.1868 \times Y' - 10.1482.$$

Calibration algorithms

To perform these calibration methods in an embedded system, the linear algebra equation set, Equation 4 or Equation 6, must be resolved. The solution can be derived simply from Cramer's rule: For the linear equation set $b = A \times x$, b is a known real vector equal to $(b_1, b_2, \ldots, b_n)^T$; A is a known real, square, full-rank matrix; and x is an unknown real vector equal to $(x_1, x_2, \ldots, x_n)^T$. The unknown elements in x can be calculated by $x_1 = \Delta_1/\Delta$, $x_2 = \Delta_2/\Delta$, . . . , $x_n = \Delta_n/\Delta$, where Δ is the determinant of matrix A, det(A); $\Delta_k = \det(A_k)$ for k = 1, 2, . . . , n; and the matrix A_k is the matrix A but with its *kth* column replaced by the vector x.

Three-point calibration algorithm

Assuming that the dimension of A is 3 × 3, Equation 8 can be determined from Equation 4, based on Cramer's rule:

$$\alpha_x = \Delta_{x1}/\Delta,\ \beta_x = \Delta_{x2}/\Delta,\ \Delta X = \Delta_{x3}/\Delta,$$
$$\alpha_y = \Delta_{y1}/\Delta,\ \beta_y = \Delta_{y2}/\Delta, \text{ and } \Delta Y = \Delta_{y3}/\Delta. \tag{8}$$

Variables in Equation 8 are defined in the sidebar on page 9.

n-point calibration algorithm

As in Equation 6, it can be assumed that the dimension of A is n × 3 with n > 3. To get the least-square solutions of the linear equation set, Equation 7 must first be rewritten as

$$\begin{pmatrix}\alpha_X\\ \beta_X\\ \Delta X\end{pmatrix} = \mathbf{A}^{-1} \times \begin{pmatrix}\mathbf{X}_1\\ \mathbf{X}_2\\ \mathbf{X}_3\end{pmatrix} \text{ and } \begin{pmatrix}\alpha_Y\\ \beta_Y\\ \Delta Y\end{pmatrix} = \mathbf{A}^{-1} \times \begin{pmatrix}\mathbf{Y}_1\\ \mathbf{Y}_2\\ \mathbf{Y}_3\end{pmatrix}, \tag{9}$$

where $\mathbf{A} = A^T \times A$, $(\mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3)^T = A^T \times (X_1, X_2, X_3)^T$, and $(\mathbf{Y}_1, \mathbf{Y}_2, \mathbf{Y}_3)^T = A^T \times (Y_1, Y_2, Y_3)^T$. Then, based on Cramer's rule, Equation 10 can be determined:

$$\alpha_x = \Delta_{x1}/\Delta,\ \beta_x = \Delta_{x2}/\Delta,\ \Delta X = \Delta_{x3}/\Delta,$$
$$\alpha_y = \Delta_{y1}/\Delta,\ \beta_y = \Delta_{y2}/\Delta, \text{ and } \Delta Y = \Delta_{y3}/\Delta, \tag{10}$$

where

$$\Delta = n \times \left(a \times b - c^2\right) + 2 \times c \times d \times e - a \times e^2 - b \times d^2,$$
$$\Delta_{x1} = n \times \left(\mathbf{X}_1 \times b - \mathbf{X}_2 \times c\right) + e \times \left(\mathbf{X}_2 \times d - \mathbf{X}_1 \times e\right) + \mathbf{X}_3 \times \left(c \times e - b \times d\right),$$
$$\Delta_{x2} = n \times \left(\mathbf{X}_2 \times a - \mathbf{X}_1 \times c\right) + d \times \left(\mathbf{X}_1 \times e - \mathbf{X}_2 \times d\right) + \mathbf{X}_3 \times \left(c \times d - a \times e\right),$$
$$\Delta_{x3} = \mathbf{X}_3 \times \left(a \times b - c^2\right) + \mathbf{X}_1 \times \left(c \times e - b \times d\right) + \mathbf{X}_2 \times \left(c \times d - a \times e\right),$$
$$\Delta_{y1} = n \times \left(\mathbf{Y}_1 \times b - \mathbf{Y}_2 \times c\right) + e \times \left(\mathbf{Y}_2 \times d - \mathbf{Y}_1 \times e\right) + \mathbf{Y}_3 \times \left(c \times e - b \times d\right),$$
$$\Delta_{y2} = n \times \left(\mathbf{Y}_2 \times a - \mathbf{Y}_1 \times c\right) + d \times \left(\mathbf{Y}_1 \times e - \mathbf{Y}_2 \times d\right) + \mathbf{Y}_3 \times \left(c \times d - a \times e\right), \text{ and}$$
$$\Delta_{y3} = \mathbf{Y}_3 \times \left(a \times b - c^2\right) + \mathbf{Y}_1 \times \left(c \times e - b \times d\right) + \mathbf{Y}_2 \times \left(c \times d - a \times e\right); \text{ and}$$

$$a = \sum_{k=1}^{n} X_k'^2,\quad b = \sum_{k=1}^{n} Y_k'^2,\quad c = \sum_{k=1}^{n} X_k' \times Y_k',\quad d = \sum_{k=1}^{n} X_k',\quad e = \sum_{k=1}^{n} Y_k',$$

$$\mathbf{X}_1 = \sum_{k=1}^{n} X_k' \times X_k,\quad \mathbf{X}_2 = \sum_{k=1}^{n} Y_k' \times X_k,\quad \mathbf{X}_3 = \sum_{k=1}^{n} X_k,$$

$$\mathbf{Y}_1 = \sum_{k=1}^{n} X_k' \times Y_k,\quad \mathbf{Y}_2 = \sum_{k=1}^{n} Y_k' \times Y_k, \text{ and } \mathbf{Y}_3 = \sum_{k=1}^{n} Y_k.$$

Definitions for Equation 8

$$\Delta = \det(A) = \begin{vmatrix} X'_1 & Y'_1 & 1 \\ X'_2 & Y'_2 & 1 \\ X'_3 & Y'_3 & 1 \end{vmatrix} = (X'_1 - X'_3)\times(Y'_2 - Y'_3) - (X'_2 - X'_3)\times(Y'_1 - Y'_3)$$

$$\Delta_{x1} = \det(A_{x1}) = \begin{vmatrix} X_1 & Y'_1 & 1 \\ X_2 & Y'_2 & 1 \\ X_3 & Y'_3 & 1 \end{vmatrix} = (X_1 - X_3)\times(Y'_2 - Y'_3) - (X_2 - X_3)\times(Y'_1 - Y'_3)$$

$$\Delta_{x2} = \det(A_{x2}) = \begin{vmatrix} X'_1 & X_1 & 1 \\ X'_2 & X_2 & 1 \\ X'_3 & X_3 & 1 \end{vmatrix} = (X'_1 - X'_3)\times(X_2 - X_3) - (X'_2 - X'_3)\times(X_1 - X_3)$$

$$\Delta_{x3} = \det(A_{x3}) = \begin{vmatrix} X'_1 & Y'_1 & X_1 \\ X'_2 & Y'_2 & X_2 \\ X'_3 & Y'_3 & X_3 \end{vmatrix} = X_1\times(X'_2Y'_3 - X'_3Y'_2) - X_2\times(X'_1Y'_3 - X'_3Y'_1) + X_3\times(X'_1Y'_2 - X'_2Y'_1)$$

$$\Delta_{y1} = \det(A_{y1}) = \begin{vmatrix} Y_1 & Y'_1 & 1 \\ Y_2 & Y'_2 & 1 \\ Y_3 & Y'_3 & 1 \end{vmatrix} = (Y_1 - Y_3)\times(Y'_2 - Y'_3) - (Y_2 - Y_3)\times(Y'_1 - Y'_3)$$

$$\Delta_{y2} = \det(A_{y2}) = \begin{vmatrix} X'_1 & Y_1 & 1 \\ X'_2 & Y_2 & 1 \\ X'_3 & Y_3 & 1 \end{vmatrix} = (X'_1 - X'_3)\times(Y_2 - Y_3) - (X'_2 - X'_3)\times(Y_1 - Y_3)$$

$$\Delta_{y3} = \det(A_{y3}) = \begin{vmatrix} X'_1 & Y'_1 & Y_1 \\ X'_2 & Y'_2 & Y_2 \\ X'_3 & Y'_3 & Y_3 \end{vmatrix} = Y_1\times(X'_2Y'_3 - X'_3Y'_2) - Y_2\times(X'_1Y'_3 - X'_3Y'_1) + Y_3\times(X'_1Y'_2 - X'_2Y'_1)$$

Algorithm implementation

To implement the preceding calibration algorithms, one of the first tasks after system power up is to develop and run a software routine to perform the following steps:

- Select the display calibration points (X_k, Y_k) for $k = 1, 2, \ldots, n$ and $n \geq 3$.
- Call the touch-screen controller function to access touch-screen data.
- Touch the first point (X_1, Y_1) on the display, acquire data from the touch-screen controller, and save the touch coordinates (X'_1, Y'_1).
- Repeat the previous step to get all (X'_k, Y'_k) for $k = 2, 3, \ldots, n$ and $n \geq 3$.
- Call the function to calculate α_x, β_x, ΔX, α_y, β_y, and ΔY—for example, call Equation 10 for five-point calibration.

References

For more information related to this article, you can download an Acrobat Reader file at www-s.ti.com/sc/techlit/*litnumber* and replace *“litnumber”* with the **TI Lit. #** for the materials listed below.

Document Title	TI Lit. #
1. Wendy Fang, “Reducing Analog Input Noise in Touch Screen Systems,” Application Report	sbaa155
2. Frank L. Lewis, *Optimal Estimation: With an Introduction to Stochastic Control Theory* (John Wiley & Sons, Inc., 1986).	—

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