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RESEARCH ARTICLE

A Simulation and Evaluation Method to Estimate the Capacitive Effect on Electrode of Touch Sensors

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ABSTRACT Touch sensors are ubiquitous in daily life. As a type of touch sensor, touch buttons now face the diverse design requirements for electrode patterns. There is no method for evaluating the rationality of electrode shape during the electrode design phase. At this stage, developers typically design electrode shapes based on experience. And in the subsequent stages, multiple electrodes of different shapes will be made for testing and evaluation, and the electrode with the best effect will be selected. Due to the diversity and uncertainty of electrode shape design, this process will consume a lot of time, manpower, and material resources. There are numerous studies on simulation method of touch panels and touch screens, but due to differences in electrode structures, it is difficult to apply their results to evaluate surface sensing touch buttons. Therefore, it is meaningful to study the influence of electrode shape on sensing ability of touch buttons and find a simulation and evaluation method to guide electrode design. This research proposes a new statistical calculation method for touch mutual capacitance based on the finite element method (FEM). Subsequently, calculate the new mutual capacitance matrix within the recognition region based on the boundary conditions. Next, evaluation indicators and calculation methods are proposed based on the difference between the ideal recognition area and the simulation results. Finally, a series of experiments are designed and an experimental platform is developed to verify the simulation results.

INDEX TERMS Capacitive sensors, electrode shape, touch sensing, evaluation method.

I. INTRODUCTION

There are various types of capacitive touch sensors, and this study is interested in surface sensing touch buttons, which are sensors that recognize the touch in the sensing area. This type of sensors only determines whether there is touch or not and does not have location function, which will be referred to as area touch buttons or switches. With the development of new energy vehicles, the design requirements for the appearance of touch buttons in related applications are becoming increasingly diverse. For example, vehicle touch reading lights have strict requirements for the illumination range, so the shape of the sensing electrode will also change accordingly. One of the research directions for area touch buttons is how to design the shape of the sensing electrode to improve the sensor's ability to recognize touch without blocking out light.

Typical touch technology research involves the material, shape, and performance of sensors [1] [2]. To explore the influence of shape in research, it is necessary to make physical objects after designing the shape. This method is costly and needs to spend a spending much time making different shaped electrodes. There have been studies on simulation and evaluation methods for touch sensing, such as [3], [4], [5], [6], and [7], but their research objects are touch screens and touch panels. Due to the significant differences in electrode structures, these simulation and evaluation methods cannot be

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extended to area touch buttons. Research on simulation and evaluation methods for touch buttons is few, and mainly in the direction of circuit design [8], [9]. Therefore, it is meaningful to explore a simulation and evaluation method to estimate the impact of sensing electrode shape on touch sensing ability.

In Section II, existing finite element method (FEM) based simulation methods, the new mutual capacitance simulation calculation method proposed in this study combined with FEM, and the method of evaluating touch sensing ability using simulation results under boundary conditions will be presented separately. And the next section will present a series of designed validation experiments and the developed experimental platforms. Meanwhile, the proposed simulation and evaluation methods will be compared and analyzed with simulation software using FEM and instrument measurement results. The final section will summarize the research, discuss its limitations, and look forward to future research directions.

II. PROPOSED SIMULATION AND EVALUATION METHOD

In our project, the touch electrodes of interest are hollow rectangles with side lengths from 20 to 80 mm, and the frequency range of interest is 100kHz to 1MHz. Due to the small size of these panels compared to the wavelength, full wave finite element simulation is not required, and quasistatic solver in an infinite medium is sufficient.

Capacitive effect will occur between any two charged bodies. Therefore, the capacitance matrix can be used to describe the capacitance distribution between charged bodies and the relationship between charge and voltage, as shown in (1).

$$\begin{bmatrix} Q_1 \\ \vdots \\ Q_n \end{bmatrix} = \begin{bmatrix} C_{11} & \cdots & C_{1n} \\ \vdots & \ddots & \vdots \\ C_{n1} & \cdots & C_{nn} \end{bmatrix} \begin{bmatrix} V_1 \\ \vdots \\ V_n \end{bmatrix} \tag{1}$$

In Equation (1), Q_i and V_i represent the charge and voltage of the charged body i respectively. When $m \neq n$, C_{mn} means the mutual capacitance between the charged body m and n. When $m = n$, C_{mn} represents the self-capacitance of the charged body. At present, there are mature simulation methods that can calculate the capacitance matrix of modeled objects. Next, we will discuss the proposed simulation and evaluation method in three parts. The first part briefly introduces the widely used FEM based capacitor simulation method. simultaneously, the problems that may arise are described when using this method for surface sensing touch button simulation. Next, based on these problems, a new simulation method is obtained by improving the traditional method. The third part discusses the evaluation method of electrode touch sensing ability using simulation results.

A. TRADITIONAL CAPACITANCE SIMULATION METHOD BASED ON FEM

In theory, with the established models, given initial and boundary conditions, equilibrium, kinematics and constitutive equations can be established to solve unknown variables. However, for slightly complex structures, the analysis will encounter complex differential equations that is difficult to solve. The emergence of FEM transforms solving these complex differential equations problems into numerical integration problems within the region. For example, the capacitance matrix in (1) can be obtained by integrating the energy density of the electric field in all region, as shown in (2) and (3).

$$C_{ii} = \frac{2}{V_i^2} \int_{\Omega} \omega_e d\Omega \tag{2}$$

$$C_{ij} = \frac{2}{V_i V_j} \int_{\Omega} \omega_e d\Omega - \frac{1}{2} \left(\frac{V_i}{V_j} C_{ii} + \frac{V_j}{V_i} C_{jj} \right) \tag{3}$$

In Equation (2) and (3), ω_e represents the energy density of the electric field, and Ω is the integration region.

Subsequently, ω_e was discretized according to the FEM approach. The objects in the entire region are divided into small triangular regions by n nodes, as shown in (4). N_i is the interpolation function associated with node i, and ω_{ei} is the electric field energy density associated with node i.

$$\omega_e = \sum_{i=1}^{n} N_i \omega_{ei} \tag{4}$$

Afterwards, based on the initial conditions (material, frequency, voltage, etc.) and boundary conditions of the simulation, an appropriate interpolation method can be selected and the numerical integration method can be used to calculate the ω_{ei}. The capacitance simulation results can be obtained by scanning and calculating the parameters of the entire region. But this simulation result is only an ideal situation derived from physical laws and numerical calculations. Through testing, it can be found that practical test results often greater than ideal values. The small differences in simulation results can be amplified in testing and evaluation. Therefore, it is necessary to introduce testing errors to optimize the simulation results before evaluation.

B. IMPROVED SIMULATION METHOD

By comparing simulation and testing conditions, it can be found that errors come from differences in simulation model precision, testing circuits and environment. In simulation, only sensing devices and structural components are generally modeled, such as the casing of induction electrodes and touch areas. It is difficult to model both the circuit and the connection type and run overall simulation analysis. In addition, the simulation conditions are an ideal environment without any interference. However, even when measured in an anechoic chamber, it is difficult to achieve the same effect as in the simulated environment. Therefore, it is rational to introduce these error variables to optimize the simulation results.

Firstly, import the models into the simulation tool and arrange it according to the actual situation, as shown in Figure 1 (a). Subsequently, a spatial coordinate system is established with the plane where the touch region is located as the z-plane and the center point of the contact region between the finger model and the touch surface in Figure 1 (b) as the origin. Recording the mutual capacitance between the finger

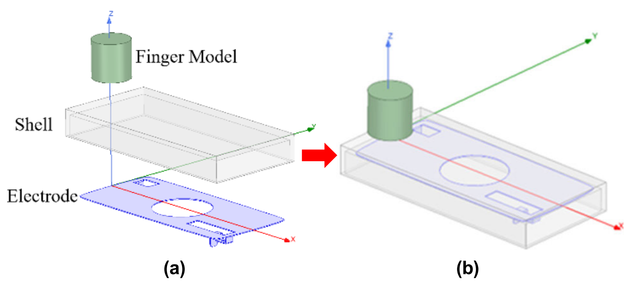


FIGURE 1. Simulation space: (a) Model files, (b) Composition model.

model and the electrode when finger model at point (x, y, z) as $C_{m(x,y,z)}$. Scanning the entire touch region with the finger model can obtain a touch capacitance matrix $C_{T(z=0)}$.

The test value for $C_{m(x,y,z)}$ is $C'_{m(x,y,z)}$. Introducing error variables Err (Err $= C'_{m(x,y,z)} - C_{m(x,y,z)}$). Through testing, it can be found that under the condition that the finger model, shell, electrode thickness and angle unchanged, Err is mainly related to the electrode size (s) and the distance (d) between the finger model and the electrode. Using circular copper sheets with the same material and thickness as the sensing electrode and different radii (r) for testing. The result of controlling variables for testing reveals a positive correlation between Err and s, and an inverse proportional relationship with d, as shown in Figure 2.

From the Err- s curve, it proves that there is a great linear relationship between Err and s when the electrode size is less than or slightly larger than the cross-sectional area of the finger model ($s \leq 0.004$ m^2), as the red curve in Figure 2 (a) shows. When the electrode size is much larger than the cross-sectional area of the finger model, the mutual capacitance will be much smaller than the self-capacitance of the electrode. The relationship between Err and s will no longer be linear, but an exponential function of gradually decreasing growth, as shown by the blue curve in Figure 2 (a). In this situation, the touch will be difficult to recognize, and the measurement of Err will also become difficult. In practical applications, such designs should be avoided, so this situation is not considered. Next, in Err - d curve, it can be observed that Err shows an approximately inverse proportional decrease with the increase of d. When d is small, the mutual capacitance is large, and the influence of peripheral interference factors is also significant. As d begins to increase, the mutual capacitance will rapidly decrease. When $d > 0.03$m, the measured value of Err has reached the lower limit of the instrument test range, which is almost 0 and constantly shaking, making it difficult to identify. Therefore, it can be approximated by 0 or a minimum value.

So, when the electrode area is smaller than the touch contact area or about the same size and within the effective touch area, the relationship between Err, s and d can be approximately described as (5) that is similar to the capacitance calculation equation for parallel plate capacitors.

$$\mathrm{Err} = \alpha' \frac{s}{d} + \mathrm{o}\,(\mathrm{Err}) \tag{5}$$

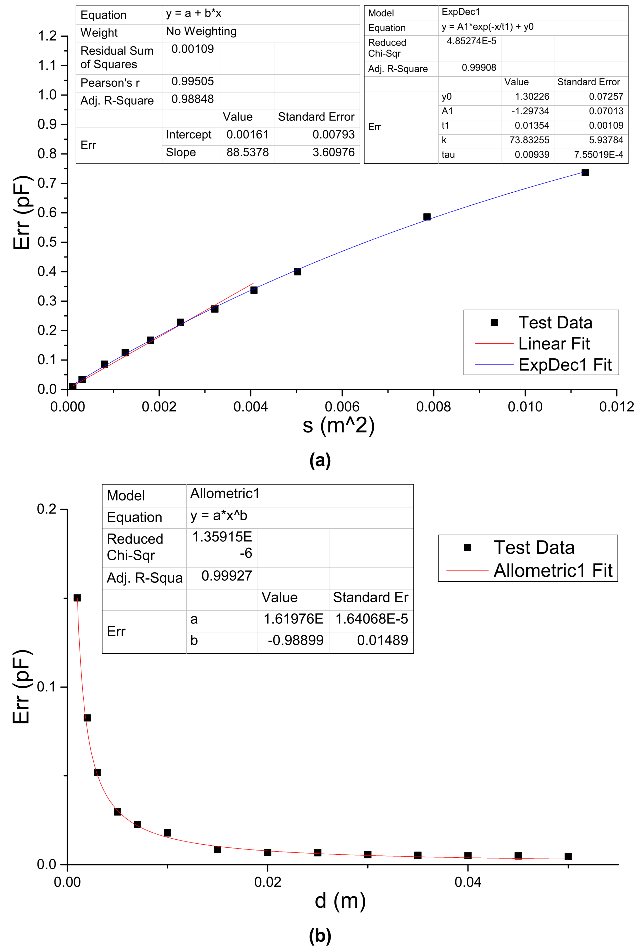


FIGURE 2. Error and fitting curves: (a) Err-s curve, (b) Err-d curve.

In Equation (5), α' is a value that can be obtained through testing related to materials and medium, and o (Err) is a value much smaller than Err and close to 0. By combining the ideas of FEM, Err can be regarded as the result of the combined action of each grid of electrode after meshing, as shown in (6).

$$\mathrm{Err} = \int_{\Omega} \alpha' \frac{s}{d} d\Omega = \sum_{\mathrm{i}=1}^{\mathrm{n}} N_{\mathrm{i}} \alpha'_{\mathrm{i}} \frac{s_{\mathrm{i}}}{d_{\mathrm{i}}} \tag{6}$$

The i represents the number of grids in region Ω. N_i can be obtained by selecting an appropriate interpolation function, and d_i is determined by the grid. Although α'_i is a quantity related to the dielectric constant (ε) of the material and can be measured, it is difficult to measure a per unit grid. Similarly, the unit grid's s_i is also difficult to measure. Due to the touch surface is mostly flat and the material used in a single simulation is fixed, the variation in dielectric constant caused by uneven touch surface and deformation during touch can be ignored, and α'_i can be considered as a constant (α'_u). Meanwhile, due to the uncomplicated electrode shape of the face touch button, each grid unit divided is very small and has little difference in size, so s_i can be approximated as a constant (s_u). In this way, Err can be approximately calculated as (7).

$$\mathrm{Err} \approx n\alpha'_{\mathrm{u}} s_{\mathrm{u}} \int_{\Omega} \frac{1}{d} d\Omega = n\alpha'_{\mathrm{u}} s_{\mathrm{u}} \sum_{\mathrm{i}=1}^{\mathrm{n}} N_{\mathrm{i}} \frac{1}{d_{\mathrm{i}}} \tag{7}$$

In this way, $\alpha'_{\mathrm{u}} s_{\mathrm{u}}$ can be obtained by measuring the electrode with a cross-sectional area smaller than the finger and dividing the result by the number of grids in the electrode. Introducing error variables Err, the touch capacitance matrix $C_{\mathrm{T(z=h)}}$ of electrodes with length L and width W can be calculated using (8).

$$\begin{aligned} C_{T(z=h)} &= \begin{bmatrix} C_{m(0,\frac{W}{2},h)} & \cdots & C_{\mathrm{m}(\frac{L}{2},\frac{W}{2},\mathrm{h})} \\ \vdots & \ddots & \vdots \\ C_{m(0,-\frac{W}{2},h)} & \cdots & C_{\mathrm{m}(\frac{L}{2},-\frac{W}{2},\mathrm{h})} \end{bmatrix} \\ &= \begin{bmatrix} C_{\mathrm{ef}(0,\frac{W}{2},\mathrm{h})} + \mathrm{Err}_{(0,\frac{W}{2},\mathrm{h})} & \cdots & C_{\mathrm{ef}(\frac{L}{2},\frac{W}{2},\mathrm{h})} + \mathrm{Err}_{(\frac{L}{2},\frac{W}{2},\mathrm{h})} \\ \vdots & \ddots & \vdots \\ C_{\mathrm{ef}(0,-\frac{W}{2},\mathrm{h})} + \mathrm{Err}_{(0,-\frac{W}{2},\mathrm{h})} & \cdots & C_{\mathrm{ef}(\frac{L}{2},-\frac{W}{2},\mathrm{h})} + \mathrm{Err}_{(\frac{L}{2},-\frac{W}{2},\mathrm{h})} \end{bmatrix} \end{aligned} \tag{8}$$

C. PROPOSED EVALUATION METHOD

After obtaining the corrected touch capacitance matrix, the touch sensing ability of electrode can be evaluated based on the characteristics of the matrix C_{T}. The proposed evaluation method includes three aspects. Firstly, the minimum value of mutual capacitance generated by fingers in the touch area should be greater than the maximum value of mutual capacitance in the critical area, which is a prerequisite for the touch button to stably recognize touch. The critical area here refers to the area of the same size and parallel to the touch area that has the smallest height and is completely unrecognizable to the touch. Its touch matrix is marked as $C_{\mathrm{T(z=H_{min})}}$. The H_{min} is the z-coordinate of the critical region. Therefore, the parameter β is used to reflect the ability of the touch button to recognize touch stably. After normalization, the calculation of β is shown in (9). Among that, max( ) and min( ) are functions that take the maximum and minimum elements of the matrix, respectively. The definition of the function relu( ) is shown in (10).

$$\beta = \mathrm{relu}\left(\frac{\min\left(C_{\mathrm{T(z=0)}}\right) - \max\left(C_{\mathrm{T(z=H_{min})}}\right)}{\max\left(C_{\mathrm{T(z=0)}}\right)}\right) \tag{9}$$

$$\mathrm{relu}\,(x) = \begin{cases} 0, & x < 0 \\ x, & x \geq 0 \end{cases} \tag{10}$$

Recording the threshold capacitance as C_{th}, $C_{\mathrm{th}} = \frac{1}{2}\left|\min\left(C_{\mathrm{T(z=0)}}\right) - \max\left(C_{\mathrm{T(z=H_{min})}}\right)\right|$. When an element in $C_{\mathrm{T}} \geq C_{\mathrm{th}}$, representing the touch at this position can be recognized; otherwise, it cannot be recognized. By scanning h from 0, the minimum h (H_{min}) with all elements in $C_{\mathrm{T(z=h)}}$ to be less than C_{th} can be found.

The second aspect is anti-interference ability which is corresponding to the fluctuation of matrix elements in C_{T}.

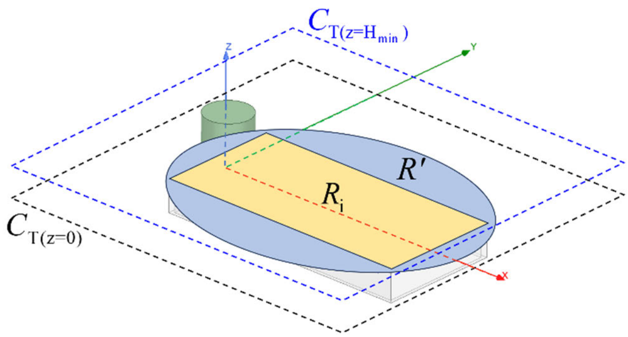


FIGURE 3. Region location diagram.

The reciprocal of normalized variance of the matrix can be used to represent this attribute. By calculating the mean μ and standard deviation σ of $C_{\mathrm{T(z=0)}}$, the normalized touch capacitance matrix $C_{\mathrm{N(z=0)}}$ can be obtained using (11). Then, the normalized variance can be obtained by calculating the variance of matrix C_{N}.

$$C_{\mathrm{N}} = \frac{C_{\mathrm{T}} - \mu}{\sigma} \tag{11}$$

The last aspect is the accuracy of touch region. It can be represented by dividing the intersection of the actual touch region (R') and the ideal touch region (R_{i}) by the union. R' refers to the region covered by elements $\geq C_{\mathrm{th}}$ in $C_{\mathrm{T(z=0)}}$. s( ) represents the function of calculating area through the number of grids. Then $\frac{\mathrm{s}(R' \cap R_{\mathrm{i}})}{\mathrm{s}(R' \cup R_{\mathrm{i}})}$ can be used to evaluate the accuracy of touch region.

Considering the above three aspects, the evaluation value E can be used to evaluate the electrode's ability to sense touch capacitance. The calculation of E is shown in (12). The k and p are proportional coefficients used to adjust the relative proportions of 3 aspects. var( ) is the function for calculating matrix variance.

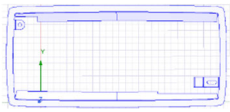
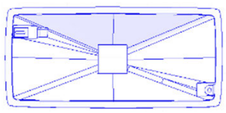
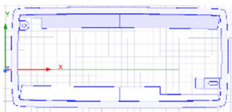
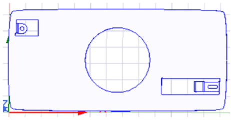
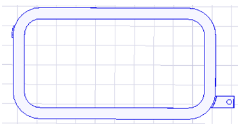
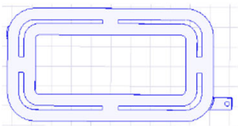
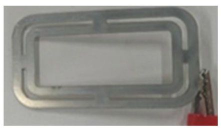
$$E = \beta\left(\frac{k}{\mathrm{var}\left(C_{\mathrm{N(z=0)}}\right)} + p\frac{\mathrm{s}\left(R' \cap R_{\mathrm{i}}\right)}{\mathrm{s}\left(R' \cup R_{\mathrm{i}}\right)}\right) \tag{12}$$

The positional relationship among $C_{\mathrm{T(z=0)}}$, $C_{\mathrm{T(z=H_{min})}}$, R' and R_{i} is shown in Figure 3.

III. EXPERIMENTS

Three experiments are designed in this section. The first experiment is finger model experiment to verify the feasibility of using the finger model to replace a human finger. The second experiment is simulation method validation experiment used to test the improvement of the simulation method. The third experiment is evaluation method validation experiment to verify the effectiveness of the evaluation method. Six electrodes with consistent sizes (65 mm * 28 mm) and different shapes designed in the project are used as interested experiment objects. Their shapes and numbers (C_ID) are shown in Table 1.

TABLE 1. **Electrodes with different shapes.**

C_ID	Model	Photo
No.1		
No.2		
No.3		
No.4		
No.5		
No.6		

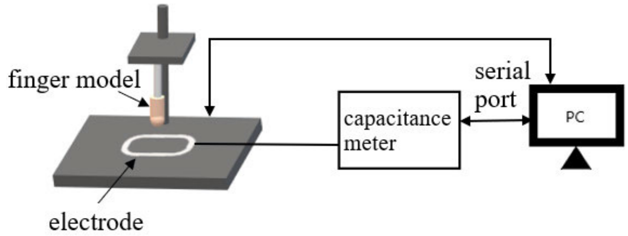


FIGURE 4. **The schematic diagram of finger model experiment.**

A. FINGER MODEL EXPERIMENT

The mutual capacitance generated when touching is in a dynamic state affected by human moisture, clothing materials, touch position, and strength. Above influencing factors cannot be controlled when directly testing with fingers [10], thus affecting the consistency and reliability of experiment results. In experiments, we use a finger model made of conductive silica gel to replace the human finger. And according to the Human Body Model (HBM) [9], connecting a 100pF capacitor between the finger model and the ground to simulate capacitance between the human body and the ground [11], [12], [13], then connecting a 1.5KΩ resistance to simulate the human body resistance [14]. The finger model uses the motor system to move and position, that to ensure the consistency of touch position and force to eliminate the influence of uncontrollable factors. The schematic diagram of this experiment is shown in Figure 4.

To reduce the number of measured points in the experiment, feature points that can represent the capacitance changes in touch area will be selected for verification and calculation by scanning the finger model in touch region along the different directions. The mutual capacitance generated by scanning the finger model along the touch plane parallel to the X and Y axes is shown in Figure 5. The scanning results of 6 electrodes are like each other. So, taking the scanning results of electrode No.1 as an example, Figure 5 (a) shows the changes of mutual capacitance during finger moves from the electrode's left midpoint to the right midpoint. In Figure 5 (a), the green circle and red arrow indicate the direction of finger movement, X axis (mx [mm]) means the coordinate of the finger, and Y axis (C [pF]) means the mutual capacitance. Figures 5 (a) and (b) show the mutual capacitance tendency in the middle lines of the electrode. Figures 5 (c) and (d) show the mutual capacitance tendency in the edge lines of the electrode. The simulation tool chosen here is ANSYS Q3D.

It can be found that in the middle lines, the mutual capacitance at the ends and the midpoint of the sensor are quite different, and the mutual capacitance of the rest points are close to the midpoint or edge points. In edge lines, the minimum value of mutual capacitance appears at the ends, and mutual capacitance of the rest points are close to the midpoint. So, its rational to pick 5 points in the middle lines and 3 points in the edge lines. Because the width of the sensors is only 28 mm, 3 points are enough to indicate the feature of mutual capacitance tendency in the direction shown in Figure 5 (b). Finally, we choose 3 feature points in the directions shown in Figure 5 (b), (c), (d), and 5 feature points in the direction shown in Figure 5 (a). The feature points are shown in Figure 6.

Two sets of test data can be obtained by touching feature points of an electrode with human finger and model finger respectively. Figure 7 shows the difference between two sets of 6 electrodes, where electrodes are marked with different color. The results show that the maximum capacitance error of the finger model and the human finger is $\leq 2.7\%$ mutual capacitance at the same point, and the average error is 0.4%. Therefore, the finger model can be used to replace the human finger for touch testing. So subsequent experiments all use the finger model.

B. SIMULATION METHOD VALIDATION EXPERIMENT

After the first experiment, simulation results based on FEM methods and feature points' test data of 6 electrodes have been obtained. By taking the absolute value of the difference between the above two sets, the difference in mutual capacitance between traditional simulation results and test data at feature points can be calculated.

Next, use the improved simulation method in Part B of Section II to calculate the simulation results and obtain new simulation data. Based on the divided grid and feature point

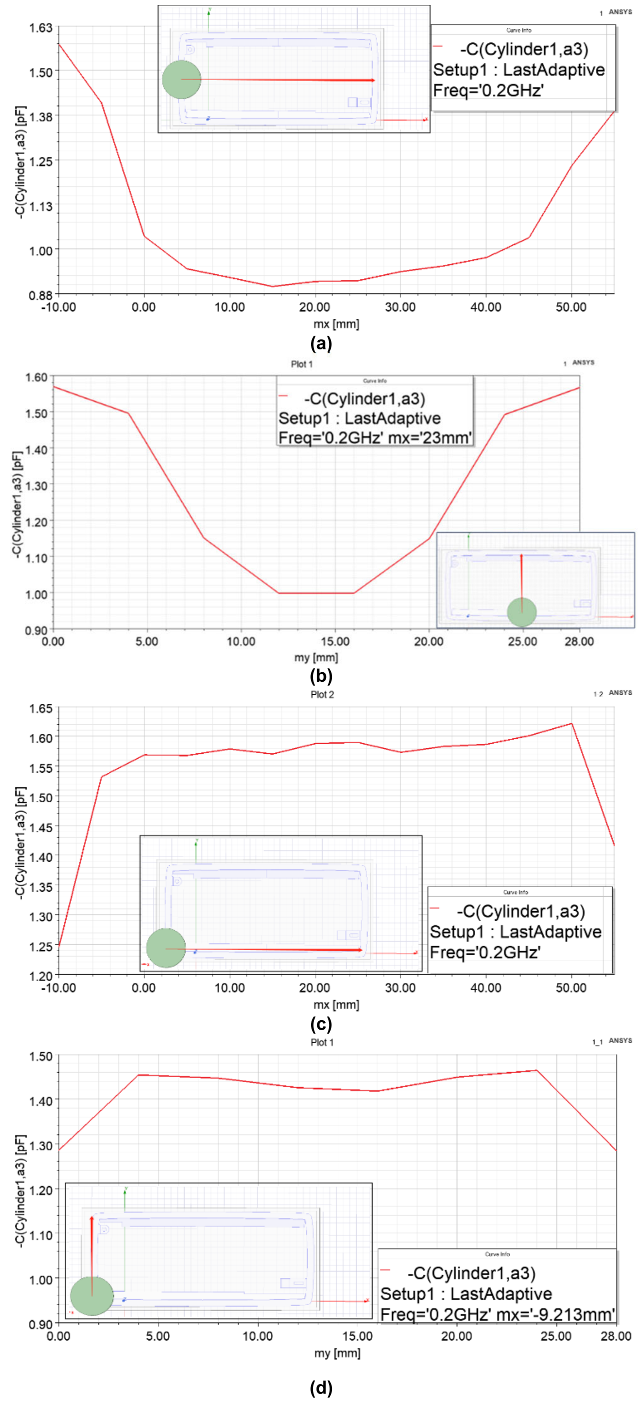


FIGURE 5. **The scanning diagram in X and Y axes directions: (a) In middle along the X-axis direction. (b) In middle along the Y-axis direction. (c) At the edge along the X-axis direction. (d) At the edge along the Y-axis direction.**

positions, it is easy to calculate the $\sum_{i=1}^{n} N_i \frac{1}{d_i}$ in (7). The $\alpha'_u s_u$ in (7) can be obtained by inputting an empirical value of 0.0116458 (unit: pF / grid) or by measuring a circular electrode with a radius of 5mm and a thickness equivalent to that of simulated electrodes. The latter is used here. The mutual capacitance value is measured by touching the circular electrode with the finger model, and then calculated using simulation tools to obtain the simulation value. Then, the absolute difference between the simulation and test is divided by the number of grids divided during simulation to obtain $\alpha'_u s_u$, which is about 0.0116375 pF/grid. This allows for the calculation of the improved simulated mutual capacitance values ($C'_{m(x,y,z)}$) of the finger model, when it moves within the touch region. Taking the electrode No.1 as an example, its improved simulation result is shown in Figure 8. Finally, calculate the difference between the improved simulation data and the test data, and compare this difference with the situation without improvement.

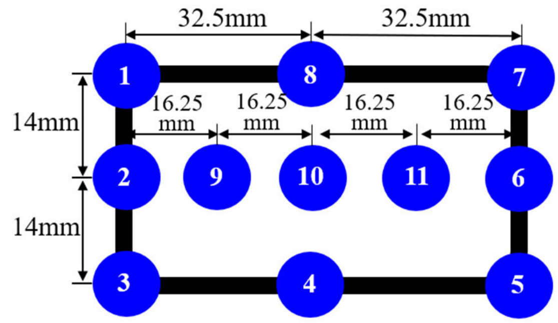


FIGURE 6. **Positions of feature points.**

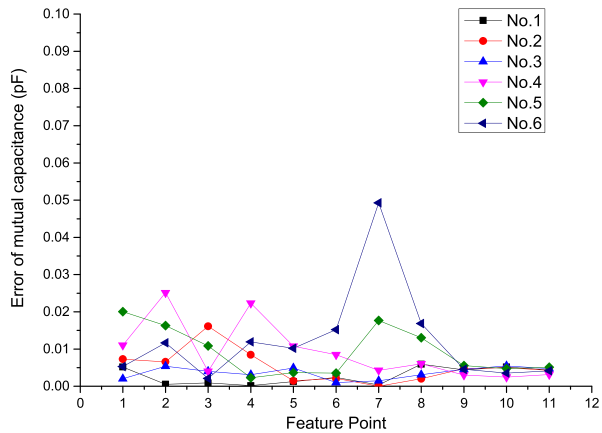


FIGURE 7. **Error comparison between the finger model and human touch.**

Figure 9 shows the gap between the traditional and improved simulation error of feature points. The solid line represents the simulation error of traditional FEM based methods, while the dashed line represents the error of improved simulation methods. Table 2 shows the statistical indicators of error between the two methods and test data. The result shows that the error of improved simulation methods is smaller in both value and fluctuation range. In other words, the improved simulation results are closer to the measured data.

C. EVALUATION METHOD VALIDATION EXPERIMENT

The touch sensing ability of an electrode would be more intuitively reflected by connecting it to recognition circuits.

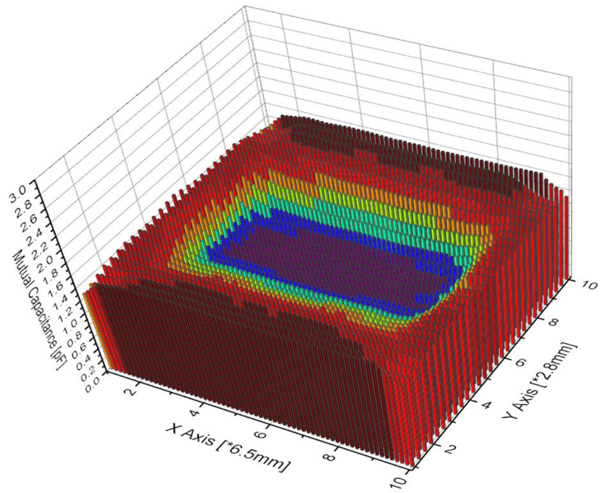


FIGURE 8. The improved scanning simulation results of electrode No.1.

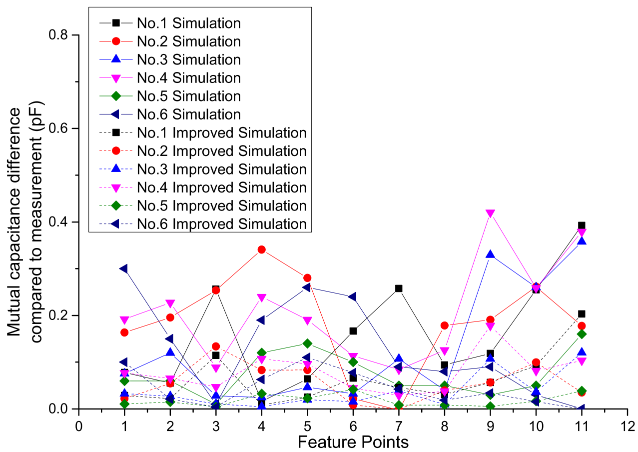


FIGURE 9. Error comparison between the traditional and improved simulation methods.

TABLE 2. Error statistic comparison between two simulation methods.

Statistics	Traditional simulation methods	Improved simulation methods
Maximum	0.42024 PF	0.20308 PF
Range	0.41771 PF	0.26198 PF
Mean	0.14900 PF	0.04988 PF
Std. Deviation	0.10955	0.04337

Based on the recognition principle of touch circuits, the microcontroller unit (MCU) can use the charging time difference to calculate the change of increased capacitance with the fixed charging voltage and current [15]. Taking the commonly used unipolar oscillation circuit for touch buttons as an example, the generated mutual capacitance is converted into the frequency change of output square wave, as Figure 10 shows. Tc and Tcp are high-voltage cycles with and without touch, respectively. This time is represented by the count

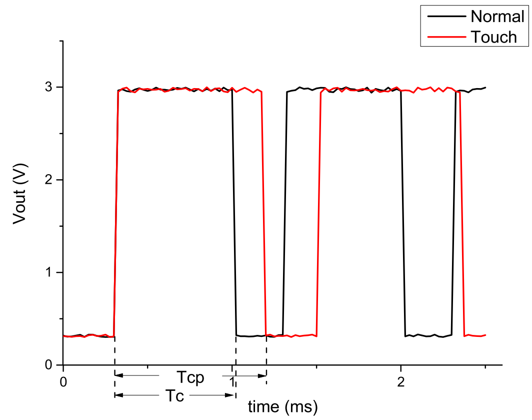


FIGURE 10. Schematic diagram of oscillation cycle changes caused by touch.

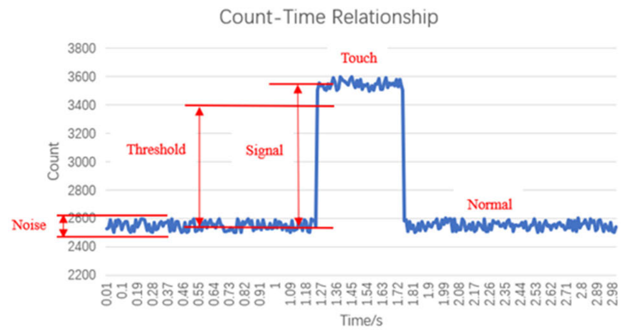


FIGURE 11. Changes of count caused by touch.

of timer inside the MCU [16], and its relationship is shown in (13).

$$\text{Count} = \left(2^{N_T} - 1\right) \frac{V_{\text{ref}} f_o}{I_{\text{DAC}}} C \tag{13}$$

In Equation (13), N_T is the number of timer bits, V_{ref} is the reference voltage, f_o is the oscillation frequency of circuit, and I_{DAC} is the modulation current of Digital to Analog Converter (DAC). When the parameters of the oscillation circuit are determined, V_{ref}, f_o and I_{DAC} are fixed values, and Count is proportional to electrode capacitance C. The control program divides it into touch state and normal state according to the change of Count, as shown in Figure 11.

Using the Count corresponding to C_{th} of each electrode as the threshold, while maintaining consistency in other circuit parameters, connect the 6 electrodes to the recognition circuit in sequence. And using the finger model to touch the valid area and invalid area (the area 5cm high from the touch surface) for the same duration at the same positions. Using MCU to record the number of touches recognized by each electrode when the finger model moves in these two areas. If the MCU recognizes touch when the finger model moves in the invalid area, it indicates that using the electrode will cause mistaken touch, that is, the design of the electrode does not meet the requirements. In this case, the Count of the electrode is recorded as 0. On the contrary, if the touch count of the

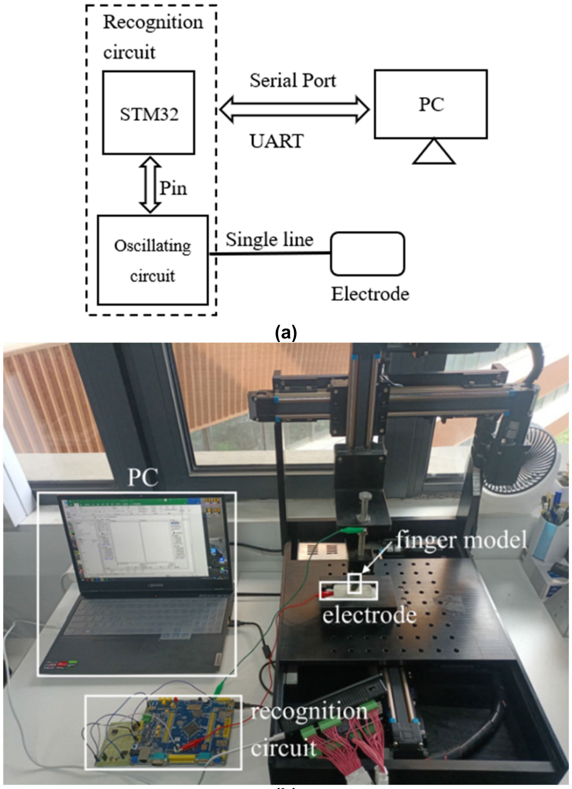


FIGURE 12. Evaluation method validation experiment: (a) Topology diagram, (b) Physical image.

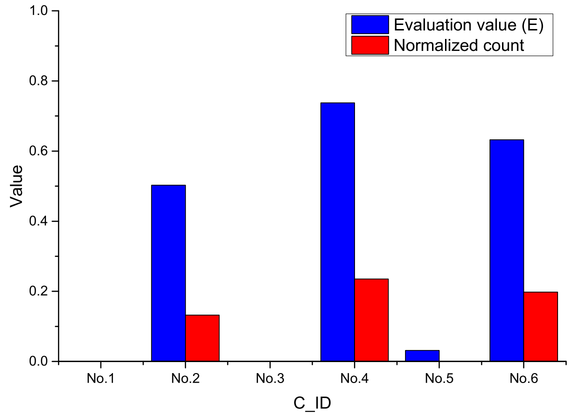


FIGURE 13. Comparison of evaluation values and touch count values.

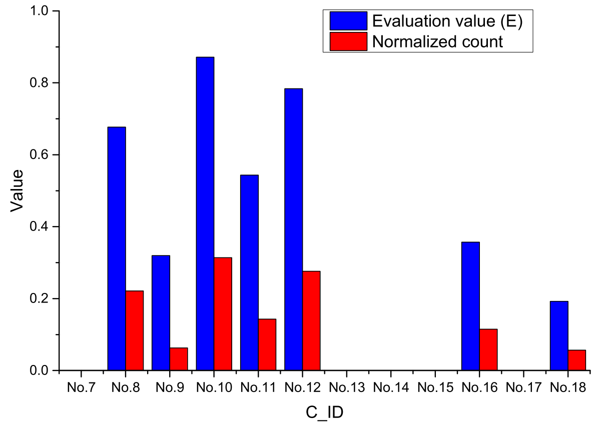


FIGURE 14. Evaluation values and touch count values comparison of the control groups.

invalid area is 0, then Count is equal to the touch count of the valid area. The topology diagram and physical image of the experiment are shown in Figure 12.

Because the evaluation value (E) in the evaluation method is a normalized value, the touch count is divided by the upper limit of the timer count set by the program for comparison with the evaluation value. This experiment uses the normalized touch count to demonstrate the ability of electrodes to sense touch. The E of 6 electrodes and the measured normalized touch counts are shown in Figure 13. Electrodes No.1 and No.3 show mistaken touch in both evaluation and testing, therefore both values are 0. Electrode No. 5 did not experience mistaken touch in evaluation, but its coefficient β was very small, resulting in mistaken touch at certain positions during the test. The E of the remaining three electrodes are consistent with the touch counts, showing a result where No.4 is better than No.6 and better than No.2.

To test the versatility of the evaluation method in electrode size, 2 sets of electrodes with different sizes are added as control groups. Table 3 shows the size of electrodes in control groups. In Table 3, column shape means the shape of the current electrode is consistent with that shown in Table 1. And column size means the length and width of each electrode. For example, electrode No.1 and No.7 have the same shape but different sizes.

TABLE 3. Information of electrodes in control groups.

C_ID	Shape	Size (length * width)
No.7	Same as No.1	51 mm * 22 mm
No.8	Same as No.2	51 mm * 22 mm
No.9	Same as No.3	51 mm * 22 mm
No.10	Same as No.4	51 mm * 22 mm
No.11	Same as No.5	51 mm * 22 mm
No.12	Same as No.6	51 mm * 22 mm
No.13	Same as No.1	79 mm * 34 mm
No.14	Same as No.2	79 mm * 34 mm
No.15	Same as No.3	79 mm * 34 mm
No.16	Same as No.4	79 mm * 34 mm
No.17	Same as No.5	79 mm * 34 mm
No.18	Same as No.6	79 mm * 34 mm

Using the same method to calculate the E and count values of the control groups, the results are shown in Figure 14. The result shows that in the control group with reduced size, except for electrode No.7, all other electrodes don't experience mistaken triggering, and the evaluation values E are consistent with the touch counts. On the other hand, the control group with increased size shows varying degrees of mistaken touch phenomenon except for electrodes No.16 and No.18. The E of electrodes 16 and 18 are also consistent with the touch counts. Therefore, this method can qualitatively evaluate the ability of electrodes to sense touch, and has universality for electrode size changes.

IV. CONCLUSION

This paper proposes a simulation and evaluation method for capacitive touch sensing electrodes. to estimate the perception ability of electrode shape on touch within the recognition region. Firstly, due to the inconsistency between current simulation methods and test results, combined with the research ideas of touch panel and touch screen simulation methods, error factors are introduced to improve the traditional simulation method. Then, using the improved simulation results combined with the principle of capacitive touch sensing, the method to evaluate the touch sensing ability of electrode is proposed. This method evaluates the electrodes from three aspects: touch effectiveness, stability, and accuracy. Finally, a series of experiments are designed and corresponding testing tools are developed to verify the effectiveness of simulation and evaluation methods. The experiment results show that the simulation data obtained by improved simulation method is closer to the measured data, and the evaluation method's results are consistent with the electrodes' performance when connecting them to a recognition circuit. The proposed methods achieve the expected goals.

The proposed simulation and evaluation method has three advantages: firstly, it can evaluate the design of electrodes shape before making, and select the design with the best evaluation results for production. This can save development time and save sampling costs. Secondly, compared to the ideal situation of traditional simulation methods, interference factors are introduced to make the simulation results closer to test results. Thirdly, based on the simulation results, the electrode evaluation method is constructed to qualitatively evaluate the rationality of electrode design.

In addition, these proposed methods also have limitations. On one hand, when the dividing grid size for electrodes is inconsistent and there is a significant difference in size between the maximum and minimum grids, the size of each grid cannot be regarded as a constant in the integration operation, and the complexity of the integration operation will increase by one dimension. Although it is rare in engineering, if electrodes are assembled from different materials, the parameter α' in (6) cannot be considered as a constant, and the integration operation will add another dimension. In this case, the calculation of error will become a triple integration of three-dimensional space, and the computational workload will increase exponentially. On the other hand, the evaluation method validation experiment only tests and verifies the hollow electrodes of interest to the project, and does not test sharp or complex shapes that are not commonly used in engineering. Therefore, if such shapes are used in electrode design, additional factors may be required in the error term of the simulation method, such as the influence of tip discharge effects. So, the limitations of these two aspects are also directions for future research.

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