Precision Performance Comparison and Improvement Initiatives for Digital Styluses

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Abstract. This paper aims to present a study on digitizer styluses, mainly focused on researching the factors affecting precision. In this article, digitizer styluses are divided into two categories, capacitive stylus and electromagnetic stylus. After that, the article explains the working principle of the two styluses, and gives a further analysis, pointing out the factors that may affect the precision. For capacitive stylus, this article will mention aspects including pen tip materials, capacitive sensors, pressure sensing, self-capacitive touch, and mutual-capacitive touch. For electromagnetic stylus, we explored aspects such as sensor types and resolution, pen tip materials and structure, circuit design and signal processing, electromagnetic interference issues, and power supply stability. Furthermore, we will base on other researchers' relevant studies on capacitive stylus and electromagnetic stylus, presenting two case studies to analyze the main factors affecting digitizer styluses. Meanwhile, this essay will also conduct a comparative analysis of the significant differences in principles between electromagnetic stylus and capacitive stylus, including their distinct performance in terms of precision. At last, the essay will conclude the overall content and conduct a try to predict the future trends of digitizer styluses in terms of precision, functionality, and user experience.

Keywords: Capacitive Stylus, Electromagnetic Stylus, Digitizer Stylus, Precision of Stylus

1 Introduction

With the development of modern digital technology, people now prefer using electronic devices for work. This change means they no longer settle for writing solely on paper, so that is why the styluses are created. It enables direct writing on digital screens, making work more convenient. The earliest digitizer styluses were developed in the 1980s. Until today, these tools have been used in different aspects by different people: engineers, artists, teachers, office workers, and even students use them to enhance productivity. Over decades of evolution, digitizer styluses have grown more precision and functional. However, current digitizer styluses still exhibit multiple limitations and need to be solved for further evolution. Up to now, digital input styluses can be divided into two main categories—capacitive styluses and electromagnetic styluses—which they work in quite different ways [1].

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This essay will focus on basic theoretical analysis, such as the definition of precision of digitizer styluses and the working principles of capacitive styluses and electromagnetic styluses. In this research, to gain an in-depth understanding of the factors affecting the precision of digitizer styluses, this essay will conduct an analysis of the impact of different components. For capacitive stylus, this article will mention aspects including pen tip materials, capacitive sensors, pressure sensing, self-capacitive touch, and mutual-capacitive touch. For electromagnetic stylus, we explored aspects such as sensor types and resolution, pen tip materials and structure, circuit design and signal processing, electromagnetic interference issues, and power supply stability. Furthermore, we will base on other researchers' relevant studies on capacitive stylus and electromagnetic stylus, presenting two case studies to analyze the main factors affecting digitizer styluses. Meanwhile, this essay will also conduct a comparative analysis of the significant differences in principles between electromagnetic stylus and capacitive stylus, including their distinct performance in terms of precision. At last, the essay will conclude the overall content and conduct a try to predict the future trends of digitizer styluses in terms of precision, functionality, and user experience.

2 Basic theory analysis

2.1 The definition of the precision of the digitizer styluses

The definition of digitizer styluses' precision refers to its ability to accurately capture and reproduce the movement track and the pressure given by the tip of the stylus. Precision is one of the most important indicators which measures the performance of the styluses., it directly influences the users' experience and work efficiency. Digitizer styluses' precision can be measured through multiple dimensions such as spatial resolution, position accuracy, and tilt sensitivity.

Spatial resolution refers to the smallest unit of change which a digitizer stylus can perceive, and it is usually expressed in dots per inch (DPI). The higher the DPI, he more details the pen can capture, thereby enabling more precise drawing and writing.

Position accuracy refers to the deviation between the position recorded and the actual position, it is usually measured in millimeters or pixels. The higher the position accuracy, the more accurate. And it will reduce the errors in writing or drawing.

tilt sensitivity refers to the ability for the stylus to detect and respond to tilt angles. The higher the sensitivity, the better the stylus can stimulate the effect of writing just like writing on real paper, such as the change in thickness of the stroke.

2.2 The basic theory of capacitive styluses

Capacitive styluses are one kind of digitizer stylus; its development is closely related to the development of the capacitive touchscreen technology. The earliest touchscreen pen appeared at 1970's, at that time, they called it optical pen. It works through a photosensitive device, when the optical pen was placed against the screen, the screen's pixels would scan the pen tip, and the optical pen would record this timestamp and send it to the computer. So that the computer could then calculate the coordinates of the optical pen on the screen based on this information, thereby displaying the trace of the optical pen [2].

Capacitive styluses are divided into two categories: active capacitive styluses and passive capacitive styluses, and there are big differences in their working methods.

Active capacitive styluses have internally integrated with batteries and electronic circuits, which they can actively generate electrical signals for interaction with touchscreens. The advantages of such styluses are that their capability to achieve more precise positioning, pressure sensitivity, and tilt detection. Typically, they emit high-frequency electrical pulses or specific electromagnetic signals through the pen tip. These signals can be received by the touchscreen and work in synergy with the touchscreen's own scanning signals. The touchscreen controller identifies the position and state of the pen tip by detecting the capacitance changes induced by the signals emitted by the capacitive stylus.

So here comes a question, when both the hand and the stylus are placed on the touchscreen, the screen will not be able to distinguish between the two, thus jumping back and forth between them. To address this, some researchers have sought to distinguish between palm touches and pen tip touches by analyzing the pattern characteristics of the two on the touchscreen. They found that the pattern of a hand on the screen has a larger radius and moves more slowly, while the pen tip is the opposite. By creating a decision tree model, the problem can be solved.

Also, there is another method to solve this problem: the Support Vector Machine (SVM) classifier. SVM is an effective classification algorithm that can distinguish among three states: no touch, finger touch, and stylus touch. The higher-frequency pulse signals sent by the stylus are digitized by an Analog-to-Digital Converter (ADC) and then input into the SVM classifier for discrimination [3].

Compared with active capacitive styluses, passive stylus usually has a simpler structure, it contains no battery or active electronic components. Their tips are made of conductive materials, such as a mixture of PDMS (polydimethylsiloxane) and conductive metal powder. When the pen tip touches or is close to the capacitive touchscreen, its conductive properties allow the human body's own electric field to couple to the touchscreen through the tip, simulating the effect of a finger touch. These styluses’ advantage are low cost and no charging needs. But its drawback is also evident, they usually cannot achieve pressure sensitivity and at the same time, they cannot solve the recognition problem mentioned earlier. Their working principle is similar to that of finger touch, both realizing induction by changing the capacitance on the screen surface [4]. A diagram of a capacitive stylus is shown in Fig.1.

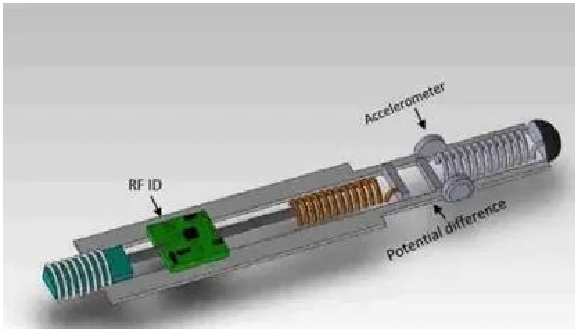

Fig. 1. A diagram of a capacitive stylus [4]

2.3 Electromagnetic styluses

The history of electromagnetic stylus technology can go back to the 1970’s. Early electromagnetic styluses were mainly applied in professional drawing and design fields, such as Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM). With the development of modern technology, electromagnetic styluses have become smaller in size and gradually lower in cost, which they then begin to enter the consumer market [5].

The working principle of electromagnetic styluses is based on the Faraday's Law of Electromagnetic Induction, which points out that when a conductor moves within a varying magnetic field, or when the magnetic field passing through a conductor loop and undergo changes, an induced electromotive force is generated in the conductor, which form induced current. In an electromagnetic stylus system, it is usually the base station device or display integrates transmission (Tx) or reception (Rx) module, while the electromagnetic stylus itself contains another module [6]. In an electromagnetic resonance (EMR) system, the coil or sensor array which placed in the display (such as the coil in an LCD panel) acts as the transmitting end, generating an electromagnetic field of a specific frequency [7]. When the electromagnetic stylus work as a receiving end or a device containing a resonant circuit and approaches these coils, the coil in the stylus will induce the energy of the electromagnetic field and generate resonance. through coil coupling, this signal is then coupled back to the receiving coils in the display, lead the electromagnetic data to be both detected and analyzed (Figure 2).

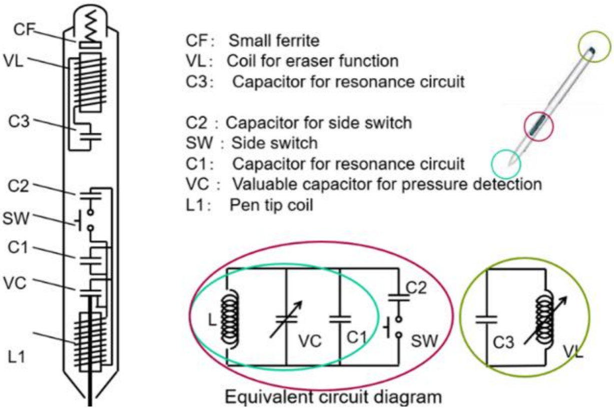

Fig. 2. A diagram of an electromagnetic stylus [7]

3 Analysis and the comparison of the factors affected precision

3.1 Capacitive styluses

Four researchers, Yao Sl, Li Lh, Sun Jq, and Yi Hj, from the School of Information Science and Technology, Northwest University, aimed to obtain an active capacitive stylus with continuous output signals and high precision. They designed a system module and a circuit module based on STM32. The system module is composed of an STM32 chip, a Bluetooth module, and a pen tip sensor module; the circuit module includes signal generation, amplification and operation, analog-to-digital conversion, frequency-selective network, and protection modules. They obtained the required signals by using a Wien bridge sine wave generating circuit, and performed analog-to-digital conversion and frequency selection on the generated sine signals. Then, they used the Bluetooth module and STM32F4 chip to connect the circuit part for controlling the output signals; the pen tip sensor collects pressure information and feeds it back to the chip, thereby changing the amplitude of the output signal to modify the output waveform. Multisim software was used to analyze and verify the generated signals, and the experimental results show that the precision of the output signal is not less than 95%. Through this research, they have greatly improved the accuracy and precision of capacitive styluses [8].

At the same time, Liang Qq from Shenzhen Goodix Technology Co., Ltd. conducted research on how to improve the precision of capacitive pens from another aspects. He found that: due to the delay of the host system and driver processing, there is usually a delay of several tens of milliseconds when a pen transmits pressure to the host via Bluetooth. This delay will cause the phenomena of missing output of the first stroke and tail trailing when lifting the stylus during the writing process of an active capacitive stylus, which greatly affects the writing experience. Therefore, he proposed adding code bits indicating pressure to the downlink coding of the capacitive stylus, and outputting the code bits when pressure is applied; the touchscreen performs real-time detection of the code bits. When it detects that the code bits change from non-existence to existence, it outputs analog pressure in advance to solve the problem of delayed output of the first stroke; when it detects that the code bits change from existence to non-existence, it terminates the pressure display in advance to solve the problem of tail trailing when lifting the stylus. Through the improvement of pressure sensing, he not only improved the precision but also enhanced the user experience [9].

The material of the pen tip will directly affect its contact area and the frictional force with the touchscreen. good electrical conductivity and moderate friction is the two basic conditions for deciding whether the pen tip is an ideal pen tip, the pen tip with good electrical conductivity will ensure stable transmission of touch signals and a moderate friction can bring the user a much more comfortable writing experience. The shape of the pen tip can also influence the precision. Stylus with a thinner tip can usually offer higher positioning accuracy although it may also reduce durability.

Capacitive Sensors. The sensitivity and resolution of the sensor directly will directly affect the stylus's precision. Capacitive touchscreen detects the styluses position when it is altering the capacitance on the touchscreen. A highly sensitive sensor can detect smaller capacitance changes, thereby increase positioning accuracy.

Linearity. Linearity is the consistency of a capacitive styluses' precision across the whole touchscreen range. The capacitive stylus which has poor linearity will have a poor precision which may vary in different areas of the screen, and lead to deviations during drawing and writing. Factors like the uniformity of the touchscreen, the design of capacitive sensors, and the optimization of signal processing algorithms may influence the linearity and lead to poor precision.

Pressure Sensing. Pressure sensing is the ability for a capacitive stylus to detect the magnitude of pressure applied on the touchscreen. With pressure sensing, users can truly use the stylus to write on the touchscreen just like writing on the real paper, Handwriting through styluses can now have more variations, such as changes in thickness and color depth. Some capacitive styluses use Electrically Coupled Resonance (ECR) technology to sense the styluses' pressure. This technology determines the magnitude of the pressure by detecting changes in capacitive coupling between the pen tip and the touchscreen. Some other designs utilize passive 3D styluses, which detect the intensity in the z-direction through algorithms without the need for actual pressure sensors [10].

Self-capacitance touch and mutual capacitance touch. Studies have shown that applying active styluses in the self-capacitance touch system of OLED TDDI (Touch and Display Driver Integration) can make the user to have a better writing experience and lead the stylus to achieve higher accuracy. The self-capacitance system has a lower RC load in terms of sensing the stylus, and that help to improve the efficiency and accuracy of signal transmission. Also, with the advancement of TDDI technology, touch and display driving functions are integrated into a single chip. This enables the touch panel to more effectively receive and process signals from the active stylus, reducing signal interference and latency, thereby improve the styluses' accuracy [11].

3.2 Electromagnetic stylus

Feng Zx from Harbin Engineering University proposed that with the continuous application and development of digitizer systems in the field of marine navigation, the use of electromagnetic pens to complete nautical chart mapping operations during the plotting process has become an urgent need. However, in large-format digitizer systems, electromagnetic pens have long been unable to be integrated into marine plotting table systems due to problems such as low precision and position offset. In order to integrate electromagnetic pens into marine plotting tables, he conducted a detailed analysis of the working principle and system composition of the digitizer based on traditional marine plotting tables, and carried out research and design on the electromagnetic pen positioning technology in the digitizer system from three aspects: positioning algorithm, hardware circuit, and software design. Based on the principle of electromagnetic induction in the digitizer system, the paper used Maxwell software—a finite element electromagnetic field analysis software developed by Ansoft Corporation—to perform three-dimensional electromagnetic field simulation of the entire electromagnetic induction digitizer. After analyzing the simulation results, the Lagrange interpolation algorithm was introduced. Through multiple simulation experiments, the induction signals generated by the grid coils of the digital tablet were collected when the energized coils were at different positions and different tilt angles. After analyzing the induction signals obtained from the simulation experiments, a method for detecting the tilt angle and a compensation algorithm for the position deviation caused by the tilt angle were finally obtained. Then, he conducted research on the hardware part of the electromagnetic pen positioning technology. The entire induced electromotive force acquisition circuit inside the digital tablet was designed based on the STM32F103C8T6 microcontroller, which included hardware circuit modules such as a power supply module, a clock module, and an interface module. Then, Keil5 software was used to complete the design of the embedded software part, including the development of embedded software programs for system initialization, register configuration, and other sections. Finally, the precision of the general electromagnetic pen using the new algorithm scheme was tested and compared with the precision of existing digitizers and calibrators. The final experimental results proved that the design can effectively improve the precision [12].

Here are some other factors that may affect precision. Sensor Type and Resolution. The core component of an electromagnetic stylus is its sensor; it is used to detect the position and pressure of the pen tip. The type and resolution of the sensor will directly affect the accuracy.

Pen tip Material and Structure. Both the material and structure of the pen tip will influence the contact area and friction force between the electromagnetic stylus and the touchscreen. A suitable pen tip material can provide a much better writing experience for the user. Also, the design for the structure of the pen tip can influence the transmission and sensing of pressure, and then influence the accuracy of pressure sensing.

Circuit Design and Signal Processing. For an electromagnetic stylus, both its internal circuit design and signal processing algorithms are essential when improving the accuracy. The performance of circuit components including low-noise amplifiers, filters, and Analog-to-Digital Converters (ADCs) will directly affect the quality and precision of signals. That means to optimize signal processing algorithms will effectively eliminate noise and interference, enhancing the accuracy of touch signals.

3.3 Comparing analysis

There are significant differences in capacitive and electromagnetic styluses' working principles, especially in terms of precision.

Positioning accuracy. For electromagnetic stylus, through accurately sensing the electromagnetic signals given back by the resonant circuit which is placed inside the stylus, electromagnetic stylus can achieve extremely high-precision positioning. Studies have shown that displays integrated with electromagnetic resonance sensors can achieve a favorable signal-to-noise ratio of 42.5 dB, which made big contribution to improve the detection accuracy. EMR systems are able to detect the tiny positional changes of the stylus on the screen, supporting pixel level precise rendering.

For capacitive stylus, the precision of passive capacitive stylus is mainly limited by the contact area of the pen tip and the size of the screen's sensing units, making it difficult to draw extremely thin lines. Although active capacitive styluses have higher precision through active signals, they may still be influenced by complex environments which have electromagnetic waves. And without doubt, their positioning accuracy is generally worse than that of electromagnetic styluses.

Pressure Sensitivity. For electromagnetic stylus, according to the pressure applied to the pen tip, an electromagnetic stylus can change the characteristics of the resonant circuit inside it and then sending back the signals of different intensities. This helps the electromagnetic stylus to achieve pressure sensitivity levels ranging from hundreds to thousands, providing delicate variations in brush strokes, such as changes in line thickness and color depth. This pressure sensing mechanism explains why electromagnetic styluses are widely favored in digital art creation and note-taking.

Capacitive stylus: Most passive capacitive styluses are lack of pressure sensitivity function. Some active capacitive stylus indirectly achieves pressure sensitivity through internal pressure sensors, but their pressure sensitivity levels and linearity are generally far lower than those of electromagnetic pens, making it difficult to provide precise brush stroke control.

Anti-interference Ability. Electromagnetic stylus: Electromagnetic signal transmission has relatively good resistance to electromagnetic interference, especially in systems with special optimized designs. The electromagnetic resonance sensors integrated inside the LCD can effectively improve the signal-to-noise ratio through optimized designs [13].

Capacitive stylus: Capacitive sensing is easy to be affected by environmental electromagnetic noise and human body charges, which may cause positioning drift or false touches, especially in humid environments or when other electronic devices are nearby.

No Need for Batteries: The passive nature of electromagnetic stylus eliminates the size, weight, and charging requirements associated with batteries, making the stylus lighter and enhancing the continuity of the user experience. Capacitive styluses, especially some active ones, require built-in batteries and regular charging, which may affect usability and the stylus' balance.

3.4 The reason for electromagnetic stylus has a higher precision

Fundamental Differences in Signal Detection Mechanisms. Electromagnetic stylus achieves positioning by sensing changes in electromagnetic fields. Electromagnetic fields enable non-contact high-precision measurement and can acquire information through multiple dimensions such as frequency and phase.

Most of the Capacitive styluses have to rely on changes in capacitance, which means, at the micro level, they may be interfered by more noise, and their essence will also limit their spatial resolution.

Integration and Optimization. Electromagnetic resonance technology is deeply placed into the display screens, for example integrating electromagnetic resonance sensors and capacitive touch sensors into LCDs. Through optimization with low-resistance materials like RX layers, it significantly improves the signal-to-noise ratio and detection sensitivity, thus help it to reach high precision.

The integration of capacitive screens is usually an independent touch layer, which has a lower degree of integration with the display layer compared to electromagnetic resonance technology. This may limit the purity of its signal detection.

Support for Pressure Sensitivity and Tilt. The resonant circuit placed inside an electromagnetic stylus is sensitive to pressure and tilt angles, so they giving back such information by altering circuit parameters. This direct physical effect makes pressure sensitivity and tilt detection to be more natural and precise.

While for capacitive stylus, as it requires additional sensors to achieve pressure sensitivity, and it is usually measured indirectly, to compared with electromagnetic styluses. Capacitive stylus will usually have lower precision and slower response speed

In summary, although due to capacitive styluses' cost-effectiveness and universality, they are widely used in consumer-grade devices, electromagnetic styluses are still better than capacitive styluses in terms of precision, high-precision positioning, delicate pressure sensitivity, and a battery-free experience.

4 Conclusion

In total, although current capacitive styluses such as Apple's Apple Pencil have already reach high precision, up to now, electromagnetic styluses like Samsung's S Pen still offer higher precision and accuracy. This is why they are generally used in places that require more precise drawing.

With the advancement of technology, capacitive stylus and touchscreen technologies will continue to improve in terms of precision, functionality, and user experience. The main challenges include the following: Although machine learning algorithms have made significant progress in improving the recognition accuracy of styluses, there are still some challenges. For example, complex environmental noise, the diversity of touch postures, and individual differences among users may affect the robustness of recognition algorithms. Future research can explore deeper neural network models to improve recognition accuracy in complex scenarios and consider introducing more dimensional data such as pressure sensing and tilt of the stylus to achieve a more refined interactive experience. At the same time, researchers are also exploring new material and structural designs to further enhance the sensitivity and durability of styluses, enabling them to provide consistent and high-precision performance in various application scenarios. Second, power consumption optimization, achieving low-power design to extend the battery life of active capacitive pens. Some touch sensors have achieved low power consumption of 6.9mw, but this is still insufficient. Third, anti-interference ability: capacitive sensors are easily to be interfered by electromagnetic wave. Future research will focus on improving their stability in complex environments. Fourth, multifunctional integration: integrating more sensors (such as pressure, tilt, biometrics, etc.) Into capacitive styluses to provide richer human-computer interaction methods. Fifth, new materials and manufacturing processes: developing new conductive materials and flexible manufacturing processes to adapt to more curved and special-shaped touchscreen designs, such as realizing capacitive touch sensing on 3d curved surfaces.

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