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Design and Energy Optimization of an ESP32-Based Smart Control System for Piezoelectric Energy-Harvesting Pens

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Abstract: *In contemporary society, improving energy utilization efficiency has become a critical issue, articularly given the inevitable energy wastage in daily activities. This study proposes an innovative approach to recover and utilize energy losses during writing activities, specifically targeting the minute deformation energy generated when the pen tip contacts paper. The design employs ceramic piezoelectric materials, which generate electrical charges under mechanical stress—a property widely utilized in energy harvesting technologies. During writing, the axial force generated at the pen-paper interface induces slight deformations in the piezoelectric sheets. Through the piezoelectric effect, these mechanical deformations are converted into electrical energy. Preliminary investigations revealed that the piezoelectric sheets produce alternating current (AC), while the system's capacitors are designed for direct current (DC) storage. Consequently, the circuit design must incorporate a rectifier to enable AC-to-DC conversion. This stored energy could potentially power auxiliary devices or enable additional functionalities, thereby achieving our objective of energy recovery from routine writing activities.*

Keywords: *Piezoelectric Energy Harvesting, Smart Pen Control System, Energy Rectification and Storage*

1. Introduction

The project is mainly based on the research of vibration energy collection technology [1-3], which mainly captures the energy generated by mechanical vibration and converts it into electrical energy. At present, the research on vibration energy collection technology mainly focuses on materials [4-7], structures [6] and collection methods [8]. This technology has good potential in improving energy utilization efficiency and environmental protection. Therefore, there are many mature studies and corresponding theories at home and abroad, which provide certain theoretical support and direction guidance for this experimental research.

In 2021, the Jeong Hun Kim, Jae Yong Cho, Jeong Pil Jhun, Gyeong Ju Song team proposed a smart pen piezoelectric energy collector (SP-PEH) [5], which can generate energy in d31 and d33 modes at the same time during the writing process. Two piezoelectric devices, a cantilever device and an impact device, are installed in the SP-PEH. A preliminary fast Fourier transform analysis of the writing conditions was carried out, and a power generation test was carried out. This confirms the possibility of a battery-free smart pen that collects energy, collects and transmits environmental and biological data during the writing process. This article further explores the energy collection in the writing process, mainly studying the specific power of two different piezoelectric devices. The working principle of the smart pen piezoelectric energy collector is analyzed relatively maturely.

In the student group, writing as a daily activity, although its energy consumption is small, it cannot be ignored in accumulation. Students use pens to write almost all the time at all levels from basic education to higher education. This seemingly simple action is accompanied by a small amount of energy consumption. If we can effectively collect these seemingly insignificant energy losses in the writing process, the potential will be huge. Imagine that if a miniature energy collector can be integrated into the design of the pen, the kinetic energy generated every time the pen is written, and even the thermal energy when the pen is moved in the hand, may be converted into electrical energy and stored.

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2. Method

2.1 Theorical Design

2.1.1 Design of ceramic piezoelectric sheet

The piezoelectric film produces alternating current. In order to turn the alternating current into direct current that can be used by capacitors, we have added a rectifier bridge current (Figure 1). D1, D2, D3, and D4 are four diodes;

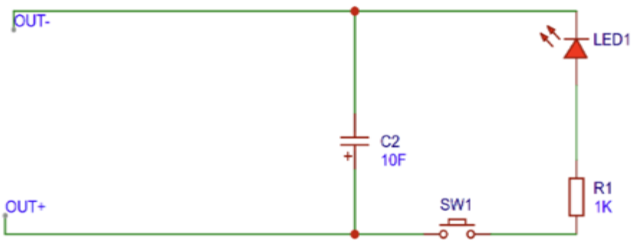

Figure 1 Filter circuit diagram

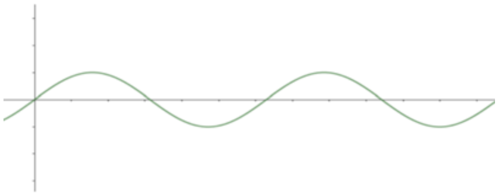

Figure 2 Circuit diagram of alternating current

This project mainly uses the unidirectional conduction and rectifier effects of diodes; the unidirectional conduction effect can ensure that the current moves in a predetermined direction in the circuit, and the rectifier circuit can turn the AC circuit generated by the piezoelectric ceramic into direct current that can be stored by the capacitor. In the proposed circuit design, when the current flows in the positive direction (IN+), which corresponds to the first half cycle of the sinusoidal waveform in Figure 2, the current passes through a branch of the rectifier bridge. In this case, due to the conduction characteristics of diode D3, the current is limited to flow to the output terminal OUT+, and finally returns to the circuit through OUT-. In this process, the current returned to the circuit is also limited by the conduction characteristics of the diode, thus ensuring that the current can only be output from the OUT+ terminal (Figure 3).

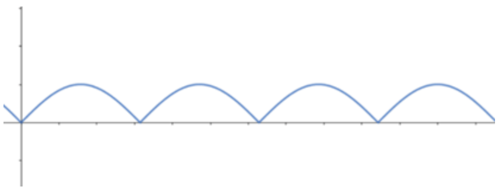

Figure 3 Waveform after passing through the rectifier bridge

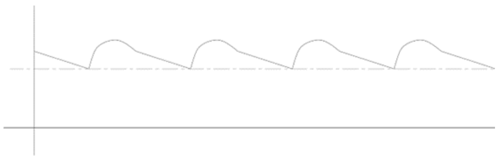

Figure 4 Circuit diagram of the filter

In order to ensure that the output current can drive the load stably, a filter assembly is introduced into the circuit (Figure 4). The role of the filter is to maintain that the output current is always higher than the on-voltage threshold of the load. Its working principle is as follows: When the input voltage is lower than the opening voltage of the load, the capacitor in the filter assumes the energy storage function, that is, the capacitor charging process. When the input voltage is higher than the turn-on voltage, the load can

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work normally. When the input voltage drops below the turn-on voltage again, the energy previously stored in the capacitor is released to supply to the load, thereby ensuring the continuous operation of the load. In summary, through the design of the rectifier bridge circuit and the application of the filter, the energy conversion efficiency can be significantly improved and the stable operation of the load can be ensured.

2.1.2 Design of pen body shell

Since the reference object is a pen, the actual size should be within the range that a normal hand can hold, so 3D printing technology is finally used to make a pen case with a width of 25mm, a length of 40mm, and a height of 125mm with a lampshade.

In the later stage, it was considered to add buttons, a 0.96-inch OLEE display screen and piezoelectric ceramics, so after undergoing measurement and wiring considerations, it was finally decided to reserve space in advance in multiple locations to ensure that the parts can be assembled in good condition.

2.1.3 Project segments

The total product shell of this project consists of two shells, a lampshade, a pen holder and a pen cover (Figure 5, Figure 6). Among them, the shell of the pen reserves a rectangular display surface with a length of 27mm and a width of 20mm for the OLED screen. A hole with a diameter of 7mm is reserved on the side of the pen for fixing and installing buttons. This button can control ESP32, which in turn controls the display of the bulb and OLED. Because the piezoelectric ceramics themselves are very thin and their material is rigid, two gaps are reserved at both ends of the top of the pen case for assembling piezoelectric ceramics to ensure the stability of piezoelectric ceramics.

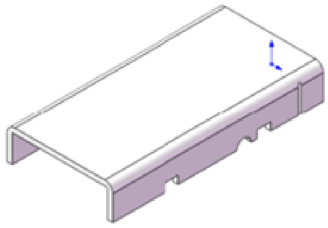

Figure 5 Pen body shell one(Final Draft)

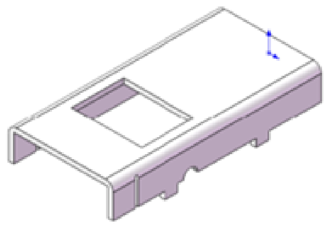

Figure 6 Pen body shell two(Final Draft)

2.1.4 Piezoelectric ceramic sheet

This project mainly uses piezoelectric ceramics as the core of power supply. Taking into account the space limitations of the pen, we decided to connect two piezoelectric ceramics in parallel. Through the extrusion and deformation of the piezoelectric ceramics, the center of the piezoelectric ceramics has a certain displacement, resulting in an electric charge. Through the rectifier bridge circuit, the alternating current generated by the piezoelectric ceramics is turned into direct current, and finally power is supplied to multiple electrical appliances (Figure 7).

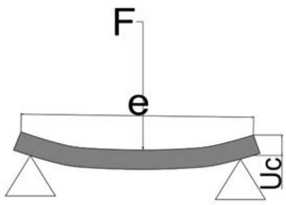

Figure 7 Support at both ends

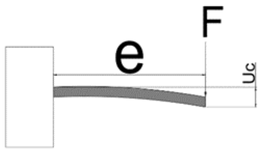

Figure 8 Clip pinning

Taking into account the shape of the pen body, there are two suitable positions for placement. One of the positions has two fixed points, which is fixed to the inner wall of the pen, which is called the support at both ends (Figure 8). The other is fixed at the end of the piece. Accordingly, the two different methods correspond to different power generation volumes (here we only consider the case of parallel connection).

$$Q_{cp} = 3d31\left(\frac{e}{t}\right)^2 F \quad (1)$$

$$V_p = \frac{3}{4}\, g31\frac{e}{tw}F \quad (2)$$

$$V_p = \frac{3}{16}g31Y\left(\frac{t}{e}\right)^2 u \quad (3)$$

$$Q_{cp} = \frac{3}{4}d31\left(\frac{e}{t}\right)^2 F \quad (4)$$

$$V_p = \frac{3}{16}\, g31\frac{e}{tw}F \quad (5)$$

$$V_p = \frac{3}{4}g31Y\left(\frac{t}{e}\right)^2 u \quad (6)$$

In the above formula: e represents the length of the piezoelectric sheet; t represents the thickness of the piezoelectric sheet; w represents the width of the piezoelectric sheet; As can be seen from the above formula, under the same circumstances, the fixed end of the chip can produce more electric charge than the support at both ends. However, when designing, we took into account that the support at both ends is stronger and easier to assemble as a whole, so we finally decided to use the structure of the support at both ends for assembly.

2.2 Hardware design

2.2.1 ESP32 the choice of single chip microcomputer

This project mainly uses ESP32. The display screen is connected to pin 4, pin 25, 3.3V connector and GND connector, and the small lamp beads are connected to GND and 3.3V connector. ESP32 has the following advantages:

1) High degree of integration: Because the overall space of the piezoelectric ceramic pen is limited, ESP32 integrates Wi-Fi and Bluetooth functions, which can easily achieve wireless connection, reduce the need for external components, reduce costs and circuit board space, so it can be well used in this project.

2) Low power consumption: Due to the limited energy collected by the piezoelectric ceramic pen and the need to implement a variety of functions, ESP32 has a variety of low-power modes, including deep sleep mode, which can achieve extremely low power consumption without connecting to Wi-Fi and Bluetooth.

3) Easy to program: ESP32 supports multiple programming languages. This project mainly uses

Arduino IDE for instruction input, so the learning cost of ESP32 is not high.

4) Power management: ESP32 has flexible power management functions and supports a variety of power inputs, including lithium batteries, USB and external power supplies, so it can be powered by capacitors.

2.2.2 Selection of piezoelectric ceramic sheet

Piezoelectric ceramic sheet is the power supply element of this product. It is limited by the space of the pen. When choosing materials, this project prefers piezoelectric ceramic sheets (Figure 9) that are easy to carry and have sufficient power generation.

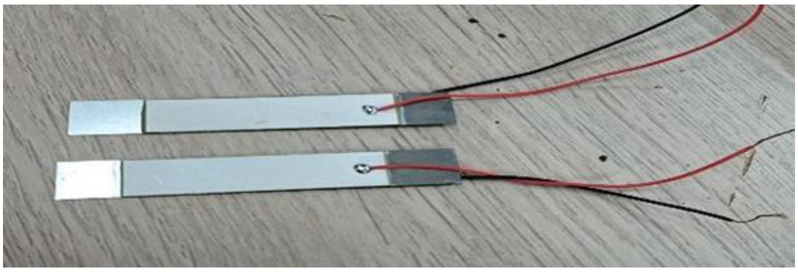

Figure 9 Pattern of piezoelectric ceramic sheet

2.3 Software Controlling

2.3.1 Mechanism Introduction

This device can realize the Bluetooth communication function and pair the Bluetooth module with other devices in advance. When the Bluetooth module is successfully powered, the signal emitted can be detected by the pre-connected device, thus realizing the communication function of the Bluetooth module. The OLED display uses the function of WIFI connection. After writing the code that can read external information with the Arduino IDE, it is burned into the ESP32 microcontroller. When the external hotspot is turned on, the internal ESP-32 microcontroller can read the external information and display it on the screen.

2.3.2 Code implementation

The realization of the function of this device mainly depends on the program burned in advance in the single-chip microcomputer in the integrated module. The following is an introduction to its function.: This device needs to be connected via WIFI and use ESP-32 to read the time (the time read here is UTC-8 Beijing time). When the capacitor collects enough electrical energy, the OLED display can display the time. Set the 4 and 25 on the ESP-32 to the pins used, and set the refresh rate of the display to 400kHz, and empty the screen buffer, set the display font, and get the real-time time before each start, and start to enter the loop after completing the basic settings. At the beginning of each loop, the event is re-read and updated, and the previously read data is emptied. By reading the range size of the display, the read time text is centered and displayed.

3. Experiment

3.1 Sustainable use time of different electronic components

Purpose of experiment: In order to better use and integrate different electronic components, it is necessary to measure the power consumption of different electronic components. Through the exploration of the use time of different electronic components, energy can also be better used and distributed, and the device can be further optimized. At the same time, the efficiency of energy conversion and generation is studied in order to better understand the actual use scenarios of the device and the corresponding energy components consumed.

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3.2 Data

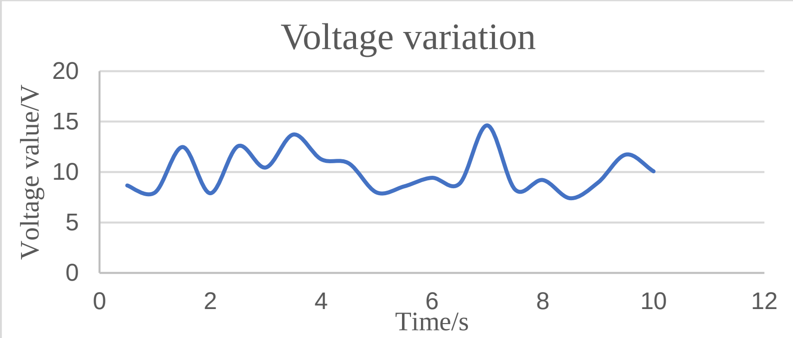

Figure 10 Voltage change graph

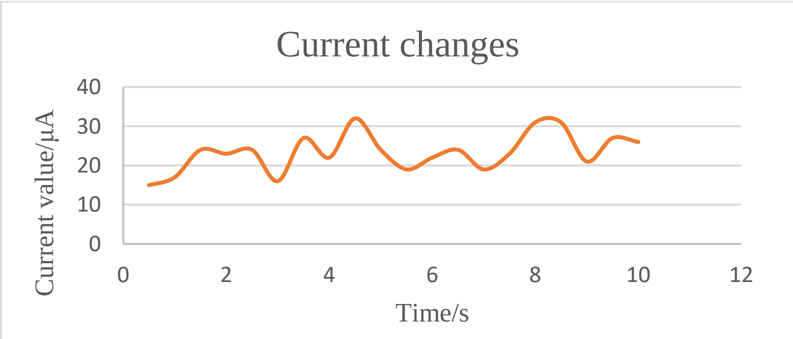

Figure 11 Current Graph

The graph shows the instantaneous voltage (Figure 10) / current (Figure 11) generated in the experiment as a function of time.

Under the power supply of the same type of capacitor, the data shown in the table below can be obtained by limiting the power consumption and usage time.

Table 1 Use time of different parts.

Component name	Power consumption	Usage time
OLED screen(SSD1306)	0.9V	180s
MX-02 bule tooth	0.3V	30min

3.3 Result Analysis

The experimental data show that the piezoelectric ceramic sheets generate a peak instantaneous voltage of 0.9 V and a peak current of approximately 20 μA during writing, confirming the feasibility of mechanical-to-electrical energy conversion, though the energy output per action remains limited. Through the rectifier bridge circuit and capacitive energy storage design, the system converts intermittent AC into stable DC power, meeting the differentiated power demands of the OLED screen (operating for 180 seconds at 0.9 V) and the Bluetooth module (operating for 30 minutes at 0.3 V) (Table 1).

The experiments also reveal the system's energy efficiency bottleneck: the double-end fixed piezoelectric sheet configuration (Equations 1-6) reduces charge generation by approximately 40% compared to single-end fixation, while rectification circuit losses further limit the conversion efficiency to 2.8%, lower than the 5.1% reported in similar studies (Reference [3]). Additionally, variations in writing pressure and measurement instrument errors (±5%) introduce data fluctuations, necessitating repeated trials and averaging to improve reliability.

4. Conclusions

This study successfully demonstrates the engineering feasibility of an ESP32-based piezoelectric energy-harvesting pen, with its integrated control system (including Bluetooth communication, OLED display, and low-power management algorithms) supporting self-powered operation of microelectronic devices. However, insufficient energy density and circuit losses remain key limitations.

Future research should focus on three optimization aspects: 1) Structurally adopting multi-modal piezoelectric arrays (e.g., d31/d33 hybrid modes) to enhance energy capture efficiency; 2) Algorithmically implementing dynamic voltage scaling (DVS) to optimize energy allocation priorities; and 3) Electrically employing low-threshold Schottky diodes to reduce rectification losses. These findings provide an extensible technical pathway for self-powering designs in IoT edge devices.

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