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Design and Implementation of Intelligent Pet Anti-Barking Collar Control System Based on Multi-Sensor Fusion

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Abstract

Traditional single-microphone anti-bark collars suffer high false alarms, poor multi-dog adaptability, missing safety safeguards and failure to pass overseas EMC certifications. This paper develops an embedded control system based on decision-level multi-sensor fusion, using STM32L4 low-power MCU integrated with MEMS audio, capacitive wearing detection and NTC temperature sensors to form a perception-decision-execution closed loop. It supports two spray volumes (0.25 mL / 0.5 mL), ±30% adaptive recognition thresholds and a 12-hour continuous-use safety lock. Verified by third-party FCC Part 15 and CE-EMC labs, the system is mass-produced for TA.TIAOM products sold on Amazon UK. Real household tests deliver an 89.3% effective correction rate, and multi-sensor joint judgment drastically reduces noise-induced misfires, providing a viable engineering solution for pet wearable behavior collars.

Keywords: multi-sensor fusion, pet smart wearables, anti-barking control, STM32L4, FCC/CE EMC, low-power embedded, adaptive threshold, safety lock, cross-border electronics

1. Introduction

1.1 Research Background

Europe owned 85 million pet dogs in 2024, bringing widespread noise disputes. Conventional single-acoustic collars reach a 22.7% false trigger rate, with severe sensor drift between −10 °C and +55 °C, fixed correction levels and no overload protection, unable to meet U.S. and EU EMC market entry rules. Decision-level multi-sensor fusion features low power draw and strong anti-interference, making it ideal for battery-powered pet wearables. This work targets both theoretical optimization and commercial compliance.

1.2 Research Status

Spray correction outperforms ultrasonic and shock modes, yet relevant embedded multi-sensor control research is scarce. Data/feature fusion demands excessive computing resources, while most existing prototypes lack EMC optimization and real-environment validation, leading to low manufacturability. Current products face high false triggers, weak environmental adaptability and incomplete safety mechanisms, which this system addresses.

1.3 Three Core Innovations

1) Architecture: Triple-sensor fusion (sound + fit detection + temperature) blocks false triggers from the judgment source.
2) Mechanism: ±30% adaptive sensitivity plus 12-hour automatic lock accommodates diverse breeds and prevents pet overstimulation.
3) Engineering: Full hardware & software EMC optimization passes FCC and CE tests; the design is commercialized with quantified real-scene performance metrics.

2. Relevant Theoretical and Key Technical Fundamentals

2.1 Basic Theory of Multi-Sensor Fusion

Multi-sensor fusion hierarchical model: Data-level fusion conducts preprocessing and fusion operations directly on original sampling sequences, retaining complete raw information but bringing large data throughput, which imposes high requirements on MCU storage and computing resources and is unsuitable for the resource constraints of this system.

1) Feature-level fusion: Extract feature parameters of each sensor signal and build feature vectors for fusion operations, consuming considerable computing resources.
2) Decision-level fusion: Each sensor independently outputs local judgment results, followed by logical fusion of multi-channel judgment results to output the final system decision. This paradigm features low computing load and strong fault tolerance, fitting low-power microcontrollers such as STM32L4, so the system adopts a decision-level fusion architecture.

Define the local judgment output of each sensor: as S_1 (effective audio event judgment), S_2 (wearing state judgment), S_3 (temperature working condition judgment), where $S_i in 0,1$, with 1 representing the corresponding condition is satisfied and 0 representing the opposite. The judgment output Y allowing the system to trigger correction actions satisfies the logical expression:

The system only permits spray correction actions when all three conditions are met: valid barking audio, normal wearing state of the device, and environmental temperature within the allowable operating range.

Basics of multi-source sensing data preprocessing: The embedded sampling link inevitably introduces high-frequency noise, temperature drift and signal jitter. This paper adopts moving average filtering to smooth original sampling sequences. Let the original sampling sequence be $x(k)$ and the sliding window length be N; the filtered output $x_f(k)$:

A fixed-length sliding window suppresses random pulse interference and realizes time sequence alignment of multi-channel sensor sampling simultaneously, eliminating logical offset caused by sampling time differences of different peripherals.

2.2 Core Sensing Detection Mechanism

1) MEMS Audio Sensor Bark Signal Identification Mechanism: Effective signals of canine barking are mainly distributed in the 250–3500 Hz frequency band, with distinguishable spectrum characteristics from low-frequency environmental background noise and human voices (Liu Y & Wang Z, 2024). The MEMS microphone converts sound pressure signals into analog voltage quantities, which are sent to ADC for digital sampling after signal amplification and band-pass filtering. The system takes signal amplitude as the main discrimination feature, superimposed with frequency band constraints to filter interference signals outside the characteristic frequency band of dog barking.
2) Capacitive Wearing Detection Mechanism: The capacitive induction sensor continuously detects the equivalent capacitance between electrodes and ground. When the device is stably worn on the pet's neck fur surface, the equivalent capacitance shifts significantly; when the device falls off and hangs in the air, the capacitance returns to the reference baseline. The MCU continuously collects the output of the capacitive induction channel and distinguishes wearing/falling-off states through threshold comparison, so as to intercept actions under no-load conditions. Ambient humidity causes baseline drift of capacitance, and the system periodically completes baseline compensation during operation to reduce detection deviation induced by environmental humidity.
3) NTC Temperature Sensor Detection Mechanism: The resistance value of NTC thermistor decreases exponentially with temperature rise, converted into voltage signals through a voltage divider circuit and sent to ADC. The resistance-temperature relationship is described by the B-value equation:

Where: R_{25} denotes the nominal resistance at 25 ℃ (Li M & Zhang H, 2023); B is the NTC material B constant; T is thermodynamic temperature. The MCU reversely solves real-time ambient temperature through ADC collected divided voltage for system working condition verification, avoiding abnormal operation risks under extreme temperature conditions.

2.3 STM32L4 Low-Power Embedded Control Technology

The STM32L4 series adopts Cortex-M4 core, supporting multi-level low-power modes including Stop1, Stop2 and Standby. It can turn off peripheral clocks and put the core into sleep, waking up relying on external interrupts or ADC events, fitting the power consumption constraints of battery-powered wearable devices. The overall machine current can drop to microampere level under system sleep mode; when sensors capture potential effective events, wake-up is triggered to enter working mode for sampling, judgment and output control.

The system adopts a closed-loop control paradigm: sensor signal collection → signal preprocessing → multi-source fusion judgment → actuator output → status feedback. After a single control cycle ends, the system enters sleep or continues cyclic sampling according to event status.

2.4 Basic Theory of Electromagnetic Compatibility

FCC Part 15 and CE-EMC stipulate mandatory test items for consumer electronic equipment such as radiated disturbance, conducted disturbance, electrostatic discharge (ESD) and electrical fast transient pulse (EFT). Radiated disturbance restricts the intensity of electromagnetic waves radiated outward by equipment; conducted disturbance restricts conducted interference at power ports; electrostatic discharge simulates electrostatic impact on human bodies during daily use. On the hardware level, PCB partition layout, ground segmentation, configuration of filter capacitors and minimization of signal loops are adopted to control electromagnetic disturbance within standard limits, which is a necessary prerequisite for equipment to realize cross-border market access.

3. Overall System Scheme and Demand Analysis

3.1 System Functional and Performance Demand Analysis

Functional Demands

1) Multi-sensor signal collection: Periodically collect acoustic signals, capacitive wearing signals and NTC temperature signals.
2) Bark event judgment: Realize effective identification of bark events based on the multi-sensor fusion framework.
3) Dual-gear spray output: Support controllable output of small dose (0.25 mL) and large dose (0.5 mL) sprays.
4) Adaptive sensitivity adjustment: Dynamic compensation of identification thresholds within ±30% of the reference value.
5) Safety locking protection: Automatically lock the spray output channel when cumulative continuous operation time reaches 12 hours.
6) Battery power detection and low-power alarm: Real-time battery level monitoring and low-voltage reminder function.
7) Man-machine interaction visualization: through red-green dual LED indicators reflecting system status.
8) Abnormal working condition protection: Forbid correction action output under extreme temperature and sensor abnormal conditions.

Performance Demands

Table 1. Core System Performance Indicators

Parameter Item	**Design Index**
Bark identification response delay	≤220 ms
Sensitivity adjustment range	±30% of reference threshold
Spray gear output	0.25 mL, 0.5 mL
Continuous safety locking duration	12 h
Operating temperature range	-10 ℃ ~ +55 ℃
Sleep overall machine current	≤12 μA
Single-battery endurance	≥14 h
Electromagnetic compatibility	Meet FCC Part 15, CE-EMC standards

Engineering Demands

Miniaturized hardware to fit pet collar mounting; lithium battery power supply; mass production feasibility; compliance with mandatory certification constraints for overseas markets.

Table 2. Comprehensive Comparison of Different Technical Schemes

Technical Scheme	**Perception Mode**	**Safety Protection Mechanism**	**Adaptive Capacity**	**Pass EMC Certification?**	**Typical False Trigger Rate**
Traditional single-audio anti-barking collar	Single MEMS microphone	No overload locking	Fixed threshold	Most fail to meet standards	22.7%
Commercial high-end single-sensor products	Single MEMS microphone	Simple timeout protection	A small number of manual gears	Partially meet standards	14.3%
Multi-sensor fusion scheme proposed in this paper	Audio + capacitive wearing detection + temperature	12-hour cumulative locking + working condition interception	±30% dynamic self-adaptation	Fully compliant	4.1%

3.2 Overall System Architecture

The system adopts a five-layer hierarchical architecture: perception layer, fusion decision layer, execution control layer, man-machine interaction layer and power guarantee layer.

- Execution Control Layer: Spray drive circuit, outputting sprays of corresponding gears according to judgment results, integrated with hardware overcurrent and overvoltage protection.
- Perception Layer: MEMS audio sensor, capacitive wearing detection sensor and NTC temperature sensor, converting physical quantities into analog electrical signals and outputting to the main controller ADC channel.
- Fusion Decision Layer: STM32L4 main controller unit, undertaking ADC sampling, signal preprocessing, multi-sensor fusion judgment and control algorithm operation.
- Execution Control Layer: Spray drive circuit, outputting sprays of corresponding gears according to judgment results, integrated with hardware overcurrent and overvoltage protection.
- Man-Machine Interaction Layer: Red-green dual LED indicators, reflecting working status, trigger alarm, low power and locking protection status.
- Power Guarantee Layer: Lithium battery power supply loop, LDO voltage regulation and power detection circuit, providing stable power supply for the whole system.

Complete system working logic: After power-on, the equipment completes peripheral initialization and sensor baseline calibration; periodically collect raw data of multi-channel sensors; execute moving average filtering preprocessing; carry out decision-level fusion judgment; output corresponding gear sprays only when all constraint conditions are satisfied; the cumulative timing module judges whether to trigger 12-hour safety locking; LEDs refresh equipment status synchronously; enter low-power sleep mode without valid events, waiting for the next event wake-up sampling.

3.3 Core Technical Difficulties and Corresponding Solutions

Difficulty 1: False triggers induced by complex environmental noise; single audio sensing cannot distinguish dog barks from environmental clutter.

Solution: Introduce dual constraints of wearing state and temperature working conditions to filter invalid trigger scenarios relying on decision-level fusion.

Difficulty 2: Significant differences in bark amplitude among dogs of different sizes; fixed thresholds fail to adapt to multiple dog breeds.

Solution: Design an adaptive threshold compensation algorithm within ±30% to dynamically adjust identification gates following environmental baselines.

Difficulty 3: Pet stress risks caused by long-term continuous operation.

Solution: Introduce a 12-hour cumulative timing automatic locking protection mechanism.

Difficulty 4: Judgment deviation induced by unsynchronized sampling time sequences of multi-channel sensors.

Solution: Unify sampling cycles to complete time sequence alignment and moving filtering processing.

Difficulty 5: Electromagnetic interference of miniaturized wearable equipment hardly meets certification standards.

Solution: PCB analog-digital partition layout, optimized grounding topology and multi-stage filter network addition.

4. Modular Design of System Hardware Circuit

The hardware is wholly divided into STM32L4 minimum system module, multi-sensor collection module, spray drive module, man-machine interaction module and power management module. PCB design strictly separates analog signal domains and digital signal domains; analog ground and digital ground are interconnected through magnetic beads at a single point to suppress coupling interference of digital circuits on weak analog sensing links.

4.1 Main Controller Minimum System Circuit

The main controller unit selects the STM32L431 low-power microcontroller. The minimum system includes external high-speed/low-speed clocks, reset circuit and debugging download circuit. Complete GPIO and ADC channel resource allocation: ADC1 is used for audio signal collection, ADC2 for NTC temperature voltage division sampling; GPIO ports realize capacitive induction detection, spray drive control and LED status output. The chip configures multiple clock domains: high-speed clocks are enabled during active events to guarantee computing efficiency, while low-speed clocks are switched in sleep mode to reduce system power consumption.

4.2 Multi-Sensor Collection Circuit

- **MEMS Audio Sensor Circuit**: The MEMS microphone outputs weak analog signals amplified by operational amplifiers, equipped with an RC band-pass filter network to filter low-frequency noise below 250 Hz and high-frequency interference above 3500 Hz; processed signals are sent to the MCU ADC input channel. A 0.1 μF decoupling capacitor is arranged adjacent to the op-amp power supply pin to suppress crosstalk of power noise on the analog audio link. (Kim J & Park S, 2022)
- **Capacitive Wearing Detection Circuit**: Reuse the MCU internal capacitive induction peripheral, with external configured induction electrodes and compensation circuits. A guard ring structure is added to electrodes to reduce detection disturbance caused by environmental humidity and static electricity; an RC filter unit restrains high-frequency electrode interference, ensuring stable output of wearing-falling-off status and avoiding frequent status jumps.
- **NTC Temperature Detection Circuit**: An NTC thermistor forms a voltage division loop with a high-precision divider resistor, and the divided output is connected to the ADC channel. A filter capacitor is paralleled at the voltage division port to suppress power supply ripple and improve temperature sampling stability. Software completes NTC parameter calibration to compensate temperature measurement errors induced by device discreteness.

4.3 Spray Drive and Protection Circuit

The spray mechanism is driven by a miniature solenoid valve, and spray dose is controlled by solenoid valve conduction duration: 120 ms conduction outputs 0.25 mL, and 240 ms conduction outputs 0.5 mL. The MCU controls solenoid valve on-off through triode-driven MOS tubes. Freewheeling diodes are paralleled at both ends of coils to absorb reverse electromotive force during power-off; current-limiting resistors are connected in series to realize hardware overcurrent protection and prevent device burnout caused by short circuits.

4.4 Man-Machine Interaction and Power Management Circuit

- Dual LED Indicator Circuit: Red and green LEDs are driven by GPIO in series with current-limiting resistors. Differentiated flashing logic is mapped to different working statuses: normal operation, spray trigger, low-power alarm and safety locking correspond to separate flashing modes respectively, realizing concise and effective man-machine interaction without a display screen.
- Power Management Circuit: Lithium battery input, LDO low-dropout linear regulator outputs stable 3.3 V system voltage. A battery voltage sampling loop is built to estimate remaining power through ADC collection of battery terminal voltage; a low-power alarm is triggered when the battery voltage drops below the set threshold. Anti-reverse connection and TVS electrostatic protection devices are added at the power input end to improve environmental reliability of the equipment.

4.5 Hardware Electromagnetic Compatibility Optimization Design

In PCB layout, analog sensing traces are kept away from strong interference sources such as solenoid valve drive loops and digital clocks; 0.1 μF ceramic decoupling capacitors are arranged adjacent to chip power supply pins; analog ground and digital ground are interconnected via magnetic beads at a single point; traces of high-current drive loops are shortened as much as possible to reduce the electromagnetic radiation loop area; ESD protection devices are added to external interfaces. Multi-layer suppression of radiated and conducted interference is realized at the hardware level, laying a hardware foundation for passing FCC Part 15 and CE-EMC tests.

5. System Software Algorithm and Program Design

Software development is based on the Keil-MDK compilation environment. The software adopts a layered modular architecture, divided into bottom driver layer, preprocessing algorithm layer, business control layer and man-machine interaction layer. The bottom driver completes configuration of GPIO, ADC, timer and interrupt peripherals; the algorithm layer realizes filtering operation and multi-source fusion judgment; the business layer realizes spray control, timing locking and adaptive threshold calculation; the interaction layer manages LED status.

5.1 Data Preprocessing Algorithm

The system sets the sampling cycle T_s=20ms, with synchronous sampling of three channels of sensors. Moving average filtering with window length N=8 is adopted for audio and temperature sampling signals to suppress random pulse noise.

Capacitive wearing detection signals add status anti-shake logic: the wearing status is updated only after consistent output of multiple consecutive samplings to avoid false status flipping caused by instantaneous interference.

5.2 Decision-Level Multi-Sensor Fusion Judgment

S_1: Audio signals pass band-pass amplitude discrimination, output 1 when reaching the audio threshold, otherwise output 0;

S_2: Capacitance detection judges the device is under wearing state and outputs 1, otherwise outputs 0;

S_3: NTC temperature measurement result falls within the -10 ℃ ~ +55 ℃ operating range and outputs 1, otherwise outputs 0.

Judgment conditions allowing spray trigger by the system:

When Y=1, the system can execute spray correction output; any unsatisfied condition directly forbids action output, thus filtering invalid actions caused by environmental noise, equipment falling off and extreme temperatures.

5.3 Adaptive Sensitivity Adjustment Algorithm

Define the reference audio identification threshold V_0; the system dynamically revises the actual working threshold V_{th} according to the environmental noise baseline, with the adjustment range constrained to $0.7V_0 \le V_{th} \le 1.3V_0$, realizing ±30% adaptive compensation.

Where Δ represents the offset of the environmental noise baseline and k is the normalized adjustment coefficient. When the environmental background noise rises, the identification threshold is automatically raised to reduce the false trigger rate; under quiet environments, the threshold is moderately lowered to guarantee effective capture of weak barking events from small dogs.

5.4 Safety Locking and Spray Gear Control Algorithm

The system maintains a cumulative continuous operation timer T_{run}, accumulating duration after each effective spray trigger. When $T_{run} \ge$12h, the system enters locking mode, forcibly shielding the spray output channel, and LEDs output locking status prompts; the timer is cleared after user reset operation, and the system restores normal working status.

The spray gear adopts a frequency self-adaptive strategy: when the barking event frequency is low within a short time window, a small dose of 0.25 mL spray is selected; when barking events occur frequently per unit time, the system switches to large-dose output of 0.5 mL to realize graded and differentiated behavioral intervention. (Zhang L & Chen Y., 2023)

5.5 Low-Power Consumption and Abnormal Processing Mechanism

The system maintains Stop2 sleep mode most of the time to reduce overall power consumption; after ADC sampling and event judgment without valid barking events, it immediately returns to sleep state. When abnormal working conditions such as sensor sampling out-of-bounds and low battery voltage occur, the spray output channel is directly closed, and LEDs output abnormal prompts.

Main software execution flow: Power-on initialization → sensor baseline calibration → wake-up sampling from sleep → filtering preprocessing → multi-sensor fusion judgment → execute spray output when conditions are met → judge cumulative working duration → update LED status → return to sleep.

6. System Testing and Result Analysis

A hierarchical test system is built; the laboratory test platform includes signal generator, acoustic test chamber, programmable high-low temperature test chamber, power consumption analyzer and EMC anechoic chamber test system. Meanwhile, commercial products of TA.TIAOM are relied on to carry out real household scenario evaluation. Tests cover function verification, performance comparison, environmental adaptability at high and low temperatures, power consumption test, third-party EMC certification and commercial scenario field measurement.

6.1 System Function Test

Item-by-item function verification is carried out on the prototype. Test items cover multi-channel sensor collection, dynamic sensitivity adjustment, dual-gear spray output, 12-hour locking protection, low-power alarm and LED status indication, all functions meeting design indicators. When the device falls off, no spray output will be triggered regardless of audio amplitude, verifying the interception logic of wearing detection; when the temperature exceeds the boundary of -10 ℃ ~ +55 ℃, the system actively forbids correction action output.

6.2 Identification Performance Comparative Test

The control group adopts the traditional single-audio anti-barking scheme, and the experimental group adopts the multi-sensor fusion scheme proposed in this paper. The test sample set includes real dog bark samples, household environmental noise, TV human voices and street background noise, with statistics of false trigger rate, missed trigger rate and average response delay. The test results are shown in the table below.

Table 3. Identification Performance Comparison

Test Scheme	**False Trigger Rate /%**	**Missed Trigger Rate /%**	**Average Response Delay /ms**
Traditional single-audio scheme	22.7	7.4	192
Multi-sensor fusion scheme of this paper	4.1	6.2	210

Comparison results show that the introduction of decision-level multi-sensor fusion significantly suppresses the system false trigger rate; the missed trigger rate rises slightly with limited increase in response delay, while the overall identification robustness is greatly improved.

6.3 Environmental Adaptability and Power Consumption Test

Three typical temperature points (-10 ℃, +25 ℃, +55 ℃) are set in a high-low temperature test chamber for continuous reliability testing. The prototype can stably complete sampling, judgment and output control within the full temperature range. The measured average sleep current is 10.7 μA, meeting the design constraint of ≤12 μA; the continuous working duration under battery power supply reaches 14.6 h, longer than the 12-hour safety locking threshold. (Wang X & Li J., 2023)

6.4 EMC Certification Test

The prototype is sent to a third-party testing institution for a full set of FCC Part 15 and CE-EMC tests; radiated disturbance, conducted disturbance, electrostatic discharge and electrical fast transient pulse all meet standard limits, qualifying the equipment for overseas market access.

6.5 Analysis of Commercial Deployment Field Measurement

The control system is engineered and deployed on TA.TIAOM brand products sold on Amazon UK. Valid user samples collected from apartment and villa household scenarios show the comprehensive effective anti-barking rate of the system reaches 89.3%. Failure samples mainly come from extremely low-volume growling of dogs and extreme scenarios with superimposed strong complex noise. Field measurement results prove the control system boasts favorable practical value under real household application environments.

6.6 Comprehensive Comparative Analysis

Compared with mainstream commercial intelligent anti-barking products on the market, the advantages of this system lie in low false trigger characteristics brought by multi-source joint verification, adaptive sensitivity adjustment, 12-hour safety locking protection and complete EMC compliance design, with verified productized deployment. The limitation of the system is that the recognition capability for extremely low-volume barks remains to be optimized.

7. Conclusion and Prospect

7.1 Full-Text Summary

Targeting the defects of traditional pet anti-barking collars including high false trigger rate, poor adaptability for multiple dog breeds, imperfect safety mechanisms and difficulty in meeting cross-border electromagnetic compatibility requirements, this paper completes an intelligent pet anti-barking control system based on decision-level multi-sensor fusion. Modular hardware circuit design is realized to complete synchronous collection of multi-channel signals including MEMS acoustic signals, capacitive wearing detection signals and NTC temperature signals; a decision-level fusion model with joint judgment of three constraints is constructed; functions such as

±30% adaptive sensitivity compensation of thresholds, graded spray output of 0.25 mL/0.5 mL and 12-hour continuous operation safety locking protection are realized. Electromagnetic compatibility optimization is completed at the hardware level, passing third-party FCC Part 15 and CE-EMC tests (Brown A & Wilson T., 2024). Comparative prototype tests show that the multi-sensor fusion architecture reduces the system false trigger rate from 22.7% to 4.1%. This control system has been deployed on cross-border e-commerce products, with a comprehensive effective anti-barking rate of 89.3% measured under real household scenarios. This paper forms innovations in perception architecture, safety control mechanism and engineering implementation, providing an important engineering reference for similar pet wearable control systems.

7.2 Research Limitations

The system still has several limitations: identification mainly relies on signal amplitude and frequency band features, resulting in limited recognition effect for extremely low-volume growling; current adaptive sensitivity only relies on environmental noise baselines without introducing machine learning models for autonomous feature learning; the system is not equipped with wireless communication interfaces, failing to realize remote statistics of behavioral data and remote parameter configuration.

7.3 Future Prospect

Subsequent research can introduce lightweight embedded machine learning models to further improve the robustness of bark event identification; add Bluetooth low-energy communication modules to realize remote parameter configuration and behavioral data recording; continuously optimize hardware volume and overall power consumption, expand more pet behavior intervention functions, and promote further iteration and upgrading of wearable intelligent pet equipment.

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