International Journal of Scientific Engineering and Science
Volume 10, Issue 11, pp. 24-28, November 2026. ISSN (Online): 2456-7361

Design of an STM32-Based Intelligent Cycling Safety Helmet System Using Multi-Sensor

Haochun Yang[1], Yerui Zhang[2], Nan Wan[3], Nenghui Xiong[4], Dongxue Jiao[5], Jicheng Yang[6], Jiangtao Ma[7]
[1,2,3,4,5,6,7]School of Medical Information, Wannan Medical University, Wuhu,Anhui, China,241002

Abstract*—Electric bicycle and motorcycle accidents occur frequently. Regular helmets can only provide passive protection and lack functions such as fall recognition, location seeking for help, and emergency information linkage. To address this issue, this paper designs an intelligent riding warning helmet based on the STM32F103C8T6 main control unit. The system is equipped with HC-SR04 ultrasonic sensor, ADXL345 acceleration sensor, light sensor module, GPS and Air780E 4G module. It uses multi-sensor fusion to detect distance, riding posture and environmental light to achieve obstacle reminder, collision and fall judgment, dim light illumination, one-click SOS and automatic alarm. Once a fall or collision is detected, the device will send the location data and pre-stored personal emergency information to the emergency contact person. The actual test shows that all functions operate stably, and the false alarm rate for falls is less than 5%. The 4G communication adopted avoids the problem of 2G network deprecation. This solution has moderate cost and can be added to existing helmets. It is suitable for ordinary commuters, delivery riders and elderly cyclists, and also provides a feasible idea for combining riding protection and pre-hospital emergency care.*

***Keywords*—** *STM32 microcontroller, multi-sensor fusion, intelligent helmet, fall detection, 4G communication, cycling safety.*

I. INTRODUCTION

At present, the number of electric two-wheel vehicles is continuously increasing, and riding safety has become a public safety issue that cannot be ignored. Data released by the Traffic Management Bureau of the Ministry of Public Security shows that in electric vehicle traffic accidents, the proportion of deaths caused by brain injuries exceeds 80% [5]. Many casualties are not caused directly by the impact at the moment, but are further exacerbated by not seeking help in time, inaccurate rescue positioning, and not wearing helmets properly. Ordinary helmets on the market can only provide passive physical protection and cannot actively sense danger. After an accident, they also cannot automatically transmit distress signals.

Now, some intelligent helmet products have appeared on the market, but many of these products focus on entertainment functions such as Bluetooth music listening and driving video recording. The design that truly focuses on safety rescue is relatively rough. The fall detection algorithms of many products have poor anti-interference ability, and when riding is bumpy or there is an emergency brake, they are prone to false alarms; some devices rely completely on mobile phone Bluetooth for communication, and once the phone is broken or disconnected from the connection, the distress function becomes invalid; similar products in foreign countries are relatively expensive, and their rescue logic does not conform to the domestic 120 and 110 emergency procedures, making it difficult to directly popularize and use [8].

Combining embedded hardware, MEMS sensors, and 4G Internet of Things communication technology, this paper designs a multi-sensor integrated intelligent warning helmet. To be honest, doing this project is not just about creating an electronic work, but also hopes to solve the pain points in real cycling: when a rider falls and loses consciousness, no one discovers them; at night, the line of sight is poor; in case of an accident, rescue personnel cannot obtain basic medical information of the injured person. This system selects STM32 as the main control, combines posture detection, obstacle distance measurement, positioning, voice sound and light warning, and 4G text message distress with each other, and also adds the function of synchronously reporting medical emergency card information. It attempts to combine embedded devices with pre-hospital emergency needs, taking into account cost, reliability, and practical usage experience [8].

II. RESEARCH BACKGROUND

A. Research Status of Intelligent Cycling Helmets

With the rapid iteration of embedded and Internet of Things technologies, various intelligent wearable devices have developed rapidly. Intelligent helmets, as a research hotspot in cycling safety equipment, have received extensive attention from scholars both at home and abroad [3].

The research on intelligent helmets started earlier in foreign countries and has already produced some mature products in industrial operations, motorcycle riding, and fire-fighting fields. However, existing products generally have several shortcomings: the products are expensive and difficult for ordinary people to afford; the equipment's positioning and communication protocol are adapted to overseas networks, and they have poor compatibility in domestic environments; the entire emergency rescue process does not conform to China's pre-hospital emergency work procedures; the algorithm model is trained for European and American road conditions and has insufficient adaptability to the complex cycling road conditions in China.

Most related domestic research focuses on Bluetooth calls, video recording, LED lighting warnings, etc., and truly focuses on safety monitoring and emergency rescue. There are

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few mature products that truly concentrate on safety monitoring and emergency rescue. Common problems of existing equipment include: the robustness of the fall detection algorithm is insufficient, and bumps and turns are prone to false triggering; the positioning module has severe performance attenuation in tunnel and building-enclosed environments; some devices do not have independent communication capabilities and must rely on the Bluetooth of the mobile phone to work, and the loss of the mobile phone will result in the loss of the rescue ability; the overall power consumption is high, and the battery life does not meet the requirements of daily cycling use; there is a lack of connection with the domestic pre-hospital emergency system, and the alarm information content is simple, unable to provide key medical information for the injured [5].In conclusion, the existing products are difficult to meet the domestic requirements for low-cost, high-reliability, and capable of realizing rescue linkage for intelligent helmets. Conducting this project research has clear practical needs and research significance.

B. *Multi-sensor Fusion Technology*

Multi-sensor data fusion technology is to combine the raw data of environmental and state collected by multiple different sensors, after filtering, calibration, and fusion operations, to obtain a more comprehensive and reliable environmental judgment result [4]. In this system, the acceleration sensor, ultrasonic sensor, light sensor, and GPS positioning module output raw data, which is sent to the STM32 main control unit for data processing.

The single ADXL345 acceleration sensor merely relies on the acceleration threshold to determine falls, which is easily interfered by road bumps and sudden braking. After introducing the multi-feature fusion strategy of posture angle and time window constraints, it can effectively distinguish normal riding disturbances from real fall events [8]; the ultrasonic sensor adds sliding window filtering to eliminate the distance measurement jump caused by road tremors; the GPS combines status verification to filter invalid positioning data. Multi-sensor fusion can reduce the misjudgement caused by the defect of a single sensor and improve the stability of the entire system in complex cycling environments.

C. *Medical Engineering Cross-Demand in Pre-hospital Emergency*

There are many serious injury cases in electric vehicle accidents, and there is a "golden ten minutes" rescue window. When the rider falls and loses consciousness, they cannot actively call for help. If rescue personnel can obtain medical information such as the accident location, the blood type of the injured, drug allergies, and underlying diseases in advance, it can effectively shorten the on-site handling and judgment time, and reduce the risk of disability and death [6]. Currently, most cycling helmets only achieve protective functions and lack an information reporting link for pre-hospital emergency. This system combines sensor detection, 4G communication, and emergency information reporting to build an intelligent helmet as a pre-hospital emergency perception terminal.

III. Research Process

A. *Overall System Design Scheme*

The main control chip of this system is selected as the STM32F103C8T6 microcontroller, with a main frequency of 72 MHz. The chip has abundant peripheral interface resources and low power consumption, making it suitable for use in small wearable devices such as helmets [2]. The entire system is divided into six units: the main control processing unit, the multi-sensor acquisition unit, the 4G wireless communication unit, the sound, light, and voice warning unit, the OLED human-computer interaction unit, and the power management unit.

The working logic of the system follows the "perception - judgment - execution" principle: various sensors continuously collect obstacle distance, three-axis acceleration, and raw GPS positioning data, which are transmitted to the STM32 for filtering processing, multi-sensor fusion, and logical determination. When the obstacle distance is too close, local voice warning is executed; when the environmental light is dim, the LED lighting is automatically turned on; when a fall or collision event is recognized, a local voice alarm is triggered and a countdown is initiated; if the countdown ends without performing a manual cancellation of the alarm operation, the Air780E 4G module sends a distress message containing latitude and longitude coordinates and personal medical emergency file to the preset emergency contact person; at the same time, the one-key SOS manual alarm channel is retained [9].

TABLE I. Main Performance Parameters of the System.

Parameter item	Indicator
Ultrasonic distance measurement range	2-450 cm
Fall detection false alarm	⩽5%
GPS positioning error in open areas	≈10 m
Communication method	Air780E 4G-Cat.1，independent SMS sending and receiving
Display unit	0.96-inch I2C OLED
Input peripherals	5 independent function buttons

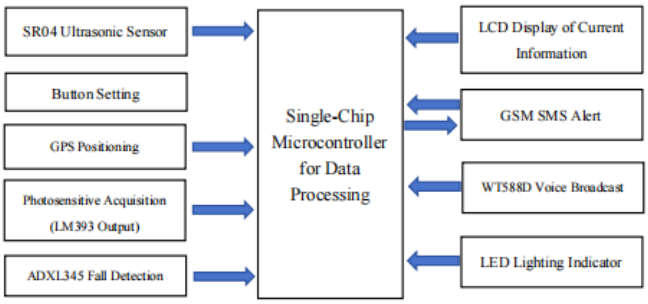


Fig. 1. Overall Hardware Block Diagram of the System.

Description: The SR04 ultrasonic sensor, key settings, GPS positioning, light-sensitive acquisition of LM393 output, ADXL345 fall detection are connected as inputs to the data processing unit of the single-chip microcomputer; the output of the single-chip microcomputer is respectively connected to the LCD for displaying current information, GSM short

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International Journal of Scientific Engineering and Science
Volume 10, Issue 11, pp. 24-28, November 2026. ISSN (Online): 2456-7361

message reminder, WT588D voice announcement, and LED for lighting indication.

B. Hardware Circuit Design

The hardware design follows the principles of helmet miniaturization, low power consumption, and modifiability. All components are selected from mature commercial modules to reduce the risk of hardware development [1].

1) Main Control Minimal System

The STM32F103C8T6 minimal system includes a power regulation circuit, reset circuit, external 8M crystal oscillator, BOOT startup configuration, and ST-LINK download circuit. The overall system externally adopts 5V direct current power supply, and is compatible with 3.3V peripherals to ensure stable power supply for sensors and communication modules.

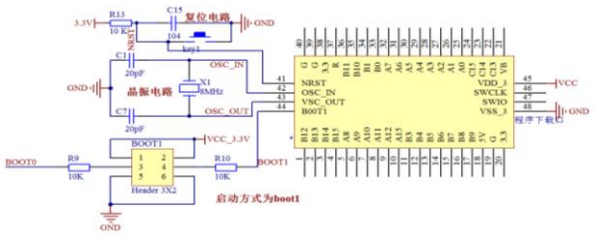


Fig. 2. Circuit schematic of the STM32 minimal system.

2) Multi-sensor Acquisition Circuit

HC-SR04 Ultrasonic Distance Measurement Module: The single-chip microcontroller outputs a 10μs trigger pulse, and the timer captures the echo signal. Based on the sound speed of 340m/s, the distance to the obstacle is calculated. Sliding window filtering is introduced to suppress data jumps caused by jitter 【4】.

ADXL345 Three-Axis Acceleration Sensor: Communicates with the single-chip microcontroller via the I2C bus, configures the ±16g measurement range, and collects the raw data of X/Y/Z three-axis acceleration. Head-on impacts and tilts will cause significant changes in the three-axis data, serving as the original data source for fall detection 【8】.

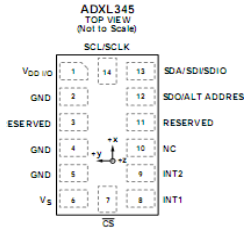


Fig. 3. Internal Functional Block Diagram and Pin Definition Diagram of ADXL345.

Photosensitive + LM393 Light Detection Circuit: The photosensitive resistor senses changes in ambient light and its resistance changes accordingly. The voltage comparator of LM393 outputs high or low levels to the microcontroller; the potentiometer can be manually adjusted to set the threshold for light and darkness, suitable for various environments such as at night, in tunnels, and on sunny days [7].

VK2828U7 GPS Positioning Module: The serial port outputs NMEA 0183 protocol data, parses the GPRMC data frame, extracts latitude, longitude, time, and positioning validity, providing location information for alarm text messages.

3) Communication and Human-Computer Interaction Circuit

The communication part uses the Air780E LTE Cat.1 module, replacing traditional SIM800 and other 2G modules, avoiding the problem of alarm failure caused by the shutdown of domestic 2G base stations. It completes the sending and receiving of Chinese text messages through the AT command set, and integrates the positioning coordinates and emergency file for the alarm text message [9].

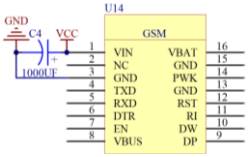


Fig. 4. Hardware Pin Diagram of Air780E Module.

Human-computer interaction: A 0.96-inch I2C interface OLED display screen shows the system's operating status; the WT588D voice chip completes obstacle warning and fall alarm voice announcements; five independent function keys are designed to achieve parameter setting, numerical addition and subtraction, one-key SOS, and alarm cancellation. Software delay anti-jitter processing is implemented to suppress mechanical key jitter and false triggering [3].

4) Power circuit

An external 5V DC power supply is input, and a power switch and power indicator circuit are configured to uniformly supply power to each module. In the productization stage, this interface can be externally connected with a lithium battery charging and discharging management module to enable outdoor portable use [1].

C. Programming for Software Design

The software development environment selects Keil MDK5, and adopts a modular hierarchical programming architecture. The main program only handles task scheduling, and various functions are encapsulated as independent sub-functions, which is convenient for later debugging, iteration, and functional addition and reduction [2].

Process summary: After the system is powered on, all serial ports and sensor modules are initialized, and the OLED displays the standby interface; the sensor collection and key scanning are executed in a loop; the obstacle distance judgment, light judgment, and fall detection logic are executed separately; corresponding voice, lighting, and SMS alarm outputs are triggered, and the process returns in a loop.

1) Main program workflow

After the system is powered on, the peripheral devices such as serial ports, I2C, and timers are initialized, and the ultrasonic wave, ADXL345, GPS, voice, and 4G modules are initialized. The OLED refreshes the standby interface. The system executes multiple tasks in parallel in a loop: reading ultrasonic distance, collecting three-axis acceleration, detecting environmental light, parsing GPS positioning, and scanning key input.

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The sensor data is sent to the logic judgment: if the distance is lower than the warning threshold, an obstacle voice reminder is executed; if the light is dim, LED lighting is turned on; if the ADXL345 detects a fall event, a countdown is initiated, and if the cancel button is not pressed after the countdown ends, the SMS sending function is called for remote alarm; pressing the SOS button directly triggers the rescue process.

2) Fall collision recognition algorithm

Simply relying on acceleration thresholds is highly susceptible to disturbances such as bumps and sudden braking, resulting in false alarms. This system adopts a combined acceleration + attitude angle + time window joint judgment algorithm [8].

Real-time read ADXL345 three-axis data, calculate the combined acceleration, and simultaneously calculate the helmet tilt angle. Dual determination conditions: within a short period, the combined acceleration exceeds the impact threshold, and the helmet attitude undergoes a significant tilt, and this abnormal state persists for a set time window, it is determined as a real fall. Ordinary riding bumps will only cause instantaneous impact, and the posture will not tilt for a long time, thereby filtering out most false triggers. After determining a fall, a countdown is initiated, and a manual cancellation alarm window is reserved to avoid SMS harassment due to misjudgment.

3) Core sub-routine

Ultrasonic distance measurement sub-routine: trigger ultrasonic emission, the timer captures the echo, sliding window filtering eliminates abnormal values, and outputs the valid distance [4];

GPS Parsing Subroutine: Receives NMEA protocol strings via serial port, extracts latitude and longitude, performs degree-minute format conversion, and is used for OLED display and SMS alerting.

Air780E SMS sending subroutine: Send AT command via serial port, configure SMS text mode, read pre-stored emergency contact numbers, GPS coordinates, and medical emergency card information, and assemble a complete alarm SMS for sending [9];

WT588D voice subroutine: Call the pre-recorded voice address, execute distance reminder and fall alarm voice playback.

IV. Analysis of Experimental Results

A. Setup of Test Environment

Hardware assembly and program burning were completed. Multiple simulation scenarios were set up to simulate various conditions encountered during real cycling. The test was divided into two parts: individual module testing and comprehensive scenario simulation testing.

TABLE II. Main Performance Parameters of the System

Test items	Number of failures
System initialization	0
Ultrasonic distance measurement collection	2
Air780E SMS sending	3
GPS positioning acquisition	2
Fall detection response	1

B. Unit Module Test

Conduct individual verification of each hardware module: The ultrasonic sensor has a small measurement deviation within the range of 2 - 450 cm; The ADXL345 can sensitively capture impact and tipping actions; The photosensitive LM393 module can accurately identify changes in light and dark and control the LED switch; In an open environment, GPS can normally resolve the location; The Air780E module can stably send Chinese text messages without being affected by the deactivation of the 2G network; The buttons, OLED, and voice modules respond normally.

C. Comprehensive Scenario Simulation

1) Obstacle Warning Test: Place obstacles at different distances, and the system will announce the distance. Close-range triggering will trigger the warning prompt;
2) Fall Detection Test: Simulate helmet jolting, sudden braking, turning, and real fall and tipping. Ordinary shaking and jolting will not trigger an alarm; After simulating a fall, the device identifies the event, and the countdown ends with the sending of a distress message. The actual measured fall detection false alarm rate is controlled within 5% [8];



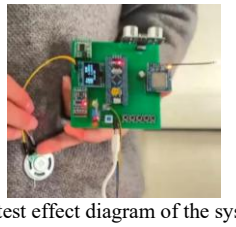
Fig. 5. Simulation effect diagram of text message alarm for fall prevention .

Description: The text message contains latitude and longitude location information as well as fall alarm prompts.

3) Dark light illumination test: Cover the light-sensitive sensor, and the LED will automatically turn on; when the light is restored, it will automatically turn off;

4) Alarm function test: Simulate a fall to trigger an automatic alarm, and simultaneously verify the SOS button for manual alarm. The text message will successfully send the latitude and longitude, as well as the preset medical information, to the target mobile phone. The received text message content and the design expectation should be consistent.

5)


Fig. 6. Physical test effect diagram of the system hardware .

The test also revealed the existing limitations of the system: GPS slows down the search for satellites and reduces positioning accuracy when buildings and large trees severely obstruct the environment; ultrasonic distance measurement

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errors increase when facing soft and sound-absorbing obstacles, which is an inherent characteristic of the sensor and can be improved through algorithm optimization and the addition of multi-source positioning in the future. In urban and suburban regular cycling scenarios, all functions of the entire system operate stably.

D. System Innovation Points

1) Communication Scheme Innovation: Adopting a 4G Cat.1 module, not relying on mobile phone Bluetooth, even if the mobile phone is damaged or lost, the helmet can still independently send a distress message, solving the pain point of traditional 2G module's network disconnection and obsolescence [9].
2) Fall Detection Algorithm Innovation: Using multi-feature combined judgment instead of simple single-threshold judgment, effectively reducing false alarms caused by cycling bumps [8].
3) Medical-Engineering Cross-functional Innovation: The alarm message is accompanied by standardized personal medical emergency files, upgrading the helmet from a protective device to a pre-collected information collection terminal for pre-rescue by rescue personnel, helping them to grasp the condition of the injured person in advance.
4) Engineering Application Innovation: The overall hardware cost is low, no need to replace the original helmet, supports direct modification and installation, suitable for students, delivery riders, and middle-aged and elderly cycling groups, with a low promotion threshold.

E. Existing Shortcomings and Optimization Prospects

The current prototype is still at the laboratory prototype stage, and there are many areas that can be optimized and improved. The plan for the future is to add a helmet wearing detection sensor, giving voice reminders when the helmet is not worn; developing a companion mini-program/APP to achieve remote parameter configuration, trajectory playback; optimizing the power consumption algorithm of the entire machine to increase the battery life; connecting with medical institutions to optimize the medical emergency information fields to make the reported information more in line with the actual needs of pre-hospital emergency services.

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This work was supported by the 2026 Provincial Undergraduate Innovation and Entrepreneurship Training Program of Wannan Medical University, “An STM32-Based Multi-Sensor Fusion Intelligent Early-Warning System for Full-Scenario Cycling Safety” (Project No. S202610368030).

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