Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 19, No. 1, 2026

Fall Detection and Safety Monitoring of The Elderly

Zhe Tang, Shang Shi, Ziteng Tian, Aojie Sun, Yingying Li, Lei Chen *

North China University of Science and Technology, Tangshan Hebei Province, 063210, China
*** Corresponding author.** Lei Chen (Email: clei@ncst.edu.cn)

Abstract: In this paper, an intelligent security monitoring system for the elderly living alone is designed and implemented to improve the efficiency of fall detection and emergency response for the elderly. The system uses STM32F407ZGT6 microcontroller as the core, combined with ICM20608 attitude detection module, ultrasonic sensor, GPS, SIM800C and 4G communication module to realize multi-modal data fusion and real-time monitoring. Through the fall recognition algorithm, Posture Analysis Method and heart rate and blood oxygen monitoring technology, the detection accuracy is improved. The system supports 4G and SMS phone dual-mode communication to ensure stable transmission in complex environments, and realizes the function of elderly location positioning and real-time viewing of elderly status through small programs. The test results show that the system has good real-time performance, accuracy and stability. This study provides an effective solution for the safety monitoring of the elderly living alone.

Keywords: Elderly Monitoring; Fall Detection; Multimodal Sensing; 4G Communications.

1. Introduction

1.1. Background

With the acceleration of population ageing in our country, it is expected that by 2025, the elderly population aged 60 and over will break through 300 million, and the proportion of elderly living alone continues to rise [1]. This group faces many security risks due to the long-term absence of children or the lack of stable care. Falls are the most common accidental injuries among the elderly and a major risk factor for life and health. The average rescue time of the elderly living alone is more than 18 hours after the fall, which leads to the risk of serious complications such as fracture and cerebral hemorrhage, and the disability rate is as high as 60% [2] . The traditional monitoring mode relying on manual intervention has problems such as lagging response and insufficient coverage, which is difficult to meet the security requirements of real-time and continuity. Problems such as chronic disease management, poor medication compliance, and increased psychological loneliness have further weakened the self-care ability of the elderly living alone, leaving them in a state of physical and psychological vulnerability. Therefore, the construction of all-weather, non-intrusive and intelligent security monitoring system has become the key to deal with the challenges of an ageing society.

Under the trend of family structure miniaturization and empty nest, the traditional family pension function is weakened, and the children's demand for remote monitoring technology is increasing. The development of Internet of things, artificial intelligence and mobile communication technology provides technical support for the popularization of intelligent monitoring equipment. The technologies of multi-modal sensor fusion, Edge Computing and cloud computing are mature, which make the integrated monitoring system based on posture recognition, heart rate monitoring and positioning tracking possible. The market has emerged integrated SOS alarm, GPS positioning and other functions of the Silver Age guard card, as well as non-contact monitoring solutions, such as Tencent 'Invisible carer' system. The government has promoted the ecological construction of smart old-age care, and promoted the large-scale deployment of smart devices in communities through pilot projects. These practices show that the society has an urgent and widespread demand for intelligent monitoring systems with high reliability, low false alarm rate and strong environmental adaptability.

At present, intelligent monitoring equipment is evolving from single function to multi-function integration, and building a closed-loop system of 'Perception-analysis-response-service'. At the hardware level, the data acquisition terminal with STM32 series microcontroller as the core, combined with a variety of sensor modules, can perceive human posture, motion characteristics and physiological parameters in multiple dimensions. In terms of communication, 4G module and low-power wide area network technology ensure stable data upload, and Cloud Platform supports large-scale equipment access and remote monitoring. The software side improves the efficiency of emergency linkage through lightweight applications. Some innovation models also incorporate the insurance mechanism into the service system to enhance user acceptance. In practical application, the community pilot data in Wuhan and other places show that the trust of the elderly in the equipment increases with the extension of the use time, and changes from passive acceptance to positive feedback on functional improvement suggestions, it reflects the feasibility of technology for the elderly.

1.2. Objectives

With the acceleration of the aging process in our country, the problem of safety guardianship for the elderly living alone has become more and more prominent. Falls are common accidental injuries in the elderly, which can lead to serious consequences such as fracture and concussion, reduce the quality of life, and increase the burden of family and social medical care. Most of the existing monitoring methods rely on manual care or simple alarm devices, which is difficult to identify falls in real time and accurately and respond quickly. Therefore, it is urgent to build an intelligent and highly automated elderly fall detection and safety monitoring system

to make up for the shortcomings of traditional monitoring modes in timeliness, accuracy and continuity. This study focuses on developing an intelligent monitoring system with high efficiency, low false alarm rate and multi-modal perception ability to dynamically monitor the posture changes of the elderly through an embedded hardware platform and a multi-source sensor fusion algorithm, when abnormal fall behavior is detected, the emergency response mechanism is quickly triggered.

The system takes the STM32F407ZGT6 microcontroller as the core, integrates the ICM20608 six-axis inertial measurement unit to obtain the acceleration and angular velocity information, and combines the ultrasonic module to detect the height mutation to improve the reliability of fall judgment. The MAX30102 heart rate and blood oxygen sensor is introduced to collect physiological parameters immediately after the event to assist in judging the user's status and avoid false alarms. It uses SIM800C GSM module to support SMS and phone alarm, and uploads the location information, fall timestamp and vital signs to ONENET Cloud Platform through 4G network, to ensure that families or rescue agencies timely grasp the situation in case of emergency. The WeChat applet is developed as a mobile terminal interactive interface, which integrates the functions of elderly location display, navigation path planning and remote calling of cameras to form a complete closed loop. The system emphasizes the edge computing ability, completes the preliminary data processing and feature extraction locally, reduces the cloud load, and shortens the response delay [4] .

The research focuses on solving the problems of high false alarm rate and poor environmental adaptability of existing Fall Detection Technologies. The attitude calculation model based on complementary fusion filter is constructed to eliminate sensor noise interference and improve the accuracy of attitude angle calculation. The multi-dimensional threshold criterion is set to comprehensively judge the effective fall event. The algorithm fully considers the daily confusing actions of the elderly, and uses the joint analysis of time domain and frequency domain to enhance the classification robustness. The system supports dual-mode communication mechanism, and 4G transmission is used by default when there is a cellular signal, and the area without cellular signal is automatically switched to short message transmission to ensure the accessibility of key information. The overall scheme takes into account portability, low power consumption and long-term stability, which is suitable for home, community and outdoor scenarios, and has strong practical value and promotion prospect.

1.3. Methodology

This study focuses on hardware selection, software development and multi-module collaborative optimization to build an efficient and stable fall detection and safety monitoring system for the elderly. At the hardware level, STM32F407ZGT6 is used as the main control microcontroller, and ICM20608 six-axis inertial measurement unit is integrated to capture subtle changes in human motion in real time. HC-SR04 ultrasonic module is introduced to assist in judging the state close to the ground, enhance the detection accuracy. The MAX30102 sensor realizes continuous monitoring of heart rate and blood oxygenation, and improves the dimension of health monitoring. The positioning is supported by the GPS module, and the remote data transmission is realized by combining the HG-307R 4G communication module SIM800C. All hardware modules are connected to the main control through standard interfaces such as I^2C, and UART to ensure stable signals and simple wiring.

Software development is based on RT-Thread real-time operating system, Task Division and resource scheduling, and give full play to its advantages of multi-thread management, memory protection and device driver framework [5] . The key tasks such as sensor data acquisition, attitude calculation, fall determination, physiological parameter analysis and communication upload are encapsulated as independent threads, and the timely response of high real-time tasks is guaranteed by priority scheduling. IMU data acquisition is triggered by 100 Hz frequency interrupt, and the attitude angle is calculated by complementary fusion filtering algorithm to suppress noise and drift. A multi-threshold dynamic decision strategy is used for fall recognition, and multiple feature quantities are integrated to avoid misjudgment. The heart rate and blood oxygenation data are processed to extract the heartbeat cycle, and the results are uploaded to the ONENET Cloud Platform through the 4G network, and the two-way interaction is realized by following the MQTT protocol.

Multi-module collaborative optimization focuses on the rational allocation of hardware resources and the timing coordination of software tasks. The DMA technology is used to realize the non-interference transmission of sensor data and reduce the CPU load. Flash stores firmware and configuration parameters, and SRAM dynamically allocates data cache and stack. Communication Link adopts dual-mode mechanism, 4G as the main channel, SMS phone for standby alarm mode, to ensure the delivery of emergency information. The front-end applet is based on WeChat ecological development, integrating map display, path navigation and remote camera call functions. Users can view videos in real time for active intervention. The system is also designed with low-power electronics, which can reduce the sampling frequency of the sensor and turn off the non-essential peripheral power supply during inactive period to extend the battery life. The above technologies together support the intelligent monitoring scheme with rapid response, strong stability and complete functions.

2. System Design and Technical Scheme

2.1. Overall System Architecture Design

The system adopts the overall architecture design of the combination of stratification and modularization to realize the accurate detection and all-round safety monitoring of the fall behavior of the elderly living alone. The hardware part of the system is composed of STM32F407ZGT6 as the main control unit, which is responsible for coordinating the data acquisition and processing tasks of each sensor module. The microcontroller is based on ARM Cortex-M4 core, which can efficiently process complex algorithms, has high computing power and real-time response characteristics, and can meet the needs of multi-source data fusion and complex algorithm operation. The peripheral module includes a six-axis inertial measurement unit (IMU) to obtain the acceleration and angular velocity information in real time, and the complementary fusion filtering algorithm can effectively improve the attitude recognition accuracy The ultrasonic module is used to assist in judging the height change of the

human body from the ground and enhance the reliability of fall judgment. The MAX30102 photoplethysmographic pulse wave sensor realizes continuous monitoring of heart rate and blood oxygenation saturation, provide physiological parameter support for health status assessment. GPS module is responsible for collecting user latitude and longitude information, to ensure that in case of emergency can quickly access to positioning.

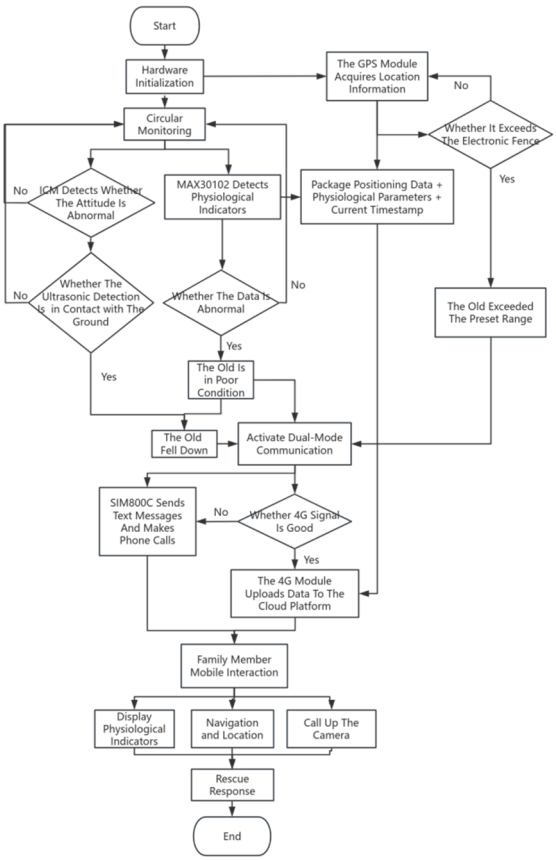


Figure 1. System Overall Flowchart

The software platform is built on the RT-Thread embedded real-time operating system, and gives full play to its multi-task scheduling and resource management advantages. The system is divided into several parallel tasks, such as data acquisition, signal processing, state judgment, alarm triggering and communication uploading. The synchronization and data transmission between tasks are realized by message queue and semaphore mechanism, ensure the timely response of critical events, and the independent execution of each task, there will be no one task trigger, the rest of the task stagnation interference occurs. Among them, the fall recognition algorithm runs in a high-priority task to ensure that the emergency process can be started immediately when an abnormal posture is detected. The system integrates SIM800C and 4G dual-mode communication modules to form a two-way communication link: under normal conditions, the user's location, Vital Signs and activity status are uploaded to the ONENET Cloud Platform in real time through the 4G module, the Guardian can open the applet at any time to view, this way real-time trigger and low power consumption; when the 4G signal is unstable or no network coverage, SIM800C will latitude and longitude, the alarm timestamp and physiological data are sent to the Guardian's mobile phone number by SMS and informed by telephone. This method is direct and efficient, which significantly improves the adaptability and reliability of the system in complex environments.

The cloud and mobile terminal realize the interactive closed-loop through WeChat applet. ONENET Platform stores and parses the data uploaded by the terminal, and opens the API interface for applets to call. Family members can view the elderly's location trajectory, heart rate trend and equipment working state in real time through the small program. After receiving the fall alarm, they can start the navigation function to plan the rescue path, at the same time, the remote command triggers the camera to open to obtain the live video to further confirm the danger. The whole system realizes the full link integration from the perception layer, the control layer, the communication layer to the application layer, and the data interaction between the modules is completed through the standardized protocol, which has good scalability and stability, it provides intelligent and networked technical support for the home safety of the elderly.

2.2. Core Hardware Module Selection and Function Description

The core hardware architecture of the system is based on the STM32F407ZGT6 microcontroller, which is based on the ARM Cortex-M4 kernel, the main frequency is 168 MHz, and the single-precision floating-point unit (FPU) and DSP instruction set are integrated, it can efficiently perform complex algorithms such as attitude calculation and sensor data fusion. Built-in 1 MB of flash memory and 192KB of SRAM, it provides ample storage and cache support for RT-Thread multitasking. Rich peripheral interfaces, including multi-channel SPI, I^2C, UART and CAN bus [6] , support ICM20608 attitude sensor, GPS, ultrasonic module and 4G communication module integrated connection. The microcontroller supports low power consumption mode, and significantly reduces power consumption in standby state, which is suitable for long-term wearing or deployed monitoring device scenarios.

ICM20608 is the core attitude sensing module, which integrates three-axis accelerometer and three-axis gyroscope. The accelerometer measurement range is ± 2 g to ± 16 g, the gyroscope measurement range is ± 250 °/s to ± 2000 °/s, and the sampling rate is up to 1 KHz, it can capture the daily activities of the elderly and sudden fall movements. Communicate with STM32 through I^2C interface, data output rate up to 32KHz, equipped with FIFO buffer to reduce the burden on the master. Combined with the complementary filter or extended Kalman filter algorithm, the attitude parameters such as pitch angle and roll angle are calculated in real time, and the fall characteristics such as rapid fall and repose are recognized. The module has strong anti-vibration interference ability, and can work stably in complex home environment to avoid misjudgment.

The ultrasonic module assists in judging the spatial changes of the environment and enhances the reliability of fall judgment. Transmitting 40KHz ultrasonic pulse and receiving the echo, the distance between the human body and the obstacle is calculated by using the time difference. The measurement range is 2 cm to 400 cm, and the accuracy is ± 3 mm. When the sudden change of acceleration is detected and the distance decreases to zero, the user is confirmed to be close to the ground, which improves the accuracy of judgment. The module connects STM32 GPIO pin with TTL level, accurately measures Echo pulse width through timer input capture function, realizes non-contact height monitoring, has

low cost and fast response, and has the advantages of high speed, low cost and high reliability, it is suitable for auxiliary criterion of multi-modal detection.

GPS module adopts ATGM336H model, supports GPS/Beidou double star positioning, outdoor meter level positioning accuracy, cold start time is less than 38 seconds, hot start time is about 1 second. STM32 receives analytic data through serial port DMA to realize real-time position tracking [7] . The function is used for emergency positioning alarm after falling, and combines ONENET Cloud Platform to realize trajectory playback and geographical fence management. When the elderly living alone go out, the GPS data and heart rate, posture information are uploaded, which provides a comprehensive state perception basis for remote monitoring.

2.3. Design of Operating System and Task Scheduling

In the elderly fall detection and safety monitoring system, real-time and multi-task collaborative processing capabilities are the core to ensure the stable operation of the system. In order to meet the requirements of concurrent execution of complex functional modules, the system uses RT-Thread real-time operating system as the basis of software architecture. RT-Thread is an open source embedded real-time multi-threaded operating system with a lightweight kernel, high real-time response and good scalability, especially suitable for resource-constrained STM32 series microcontrollers. Its minimum system occupies only 3KB Flash and 1.2 KB RAM, which significantly reduces the hardware cost while ensuring functional integrity, and fits the design requirements of wearable or portable monitoring devices [8] .

RT-Thread takes thread as the basic execution unit and supports 256-level preemptive scheduling strategy to ensure timely response of critical tasks. The system creates threads such as data acquisition, attitude calculation, heart rate monitoring, communication upload and alarm response, and sets priorities according to real-time requirements. For example, the acceleration and angular velocity data output by the attitude sensing function through ICM20608 requires high timeliness, and the corresponding data acquisition and fall discrimination threads are given high priority, an interrupt can be triggered immediately and sent to the processor for response. Low-priority threads such as GPS location information upload run in time slice rotation mode to avoid long-term occupation of CPU resources. The threads communicate with the semaphore synchronously through the Message Queue, which effectively solves the problem of competition conditions when sharing sensor data and ensures data consistency and system stability.

The rich component ecology of RT-Thread further improves the reliability and functionality of the system. The system integrates LWIP protocol stack to realize TCP/IP network communication, combines 4G module to complete networking function, and uses MQTT protocol to push the location, physiological parameters and fall timestamp of the elderly to ONENET Cloud Platform in real time. The CMSIS-DSP library is introduced through the software package management tool to optimize the operation efficiency of the complementary fusion filtering algorithm in attitude calculation. The whole system realizes efficient scheduling of hardware resources and Seamless Collaboration of Tasks under RTOS Management, which not only enhances the response ability to sudden fall events, but also reserves sufficient software space for subsequent function expansion. This architecture design based on real-time operating system makes the system have strong environmental adaptability and long-term operation stability in maintaining low-power operation, which is in line with the technical development trend of intelligent health monitoring equipment.

2.4. Design of Communication and Data Transmission Scheme

The system uses 4G communication module as the core to build a remote monitoring communication link, integrates SIM800C low-power wide-area module and ONENET Internet of things Cloud Platform to form a stable and efficient data transmission architecture. 4G module accesses China Mobile CMNET network through TCP/IP protocol stack, supports HTTP, MQTT and other application layer protocols, and takes into account real-time and reliability requirements. The device uses STM32F407ZGT6 microcontroller, which sends AT instructions through the serial port to complete network initialization, PDP context establishment and IP address acquisition, and configures APN parameters to ensure the stability of wireless connection, the CIICR instruction activates the data session to ensure the subsequent upload connectivity. The architecture is optimized for the family scene of the elderly living alone, effectively adapts to the weak signal environment, and improves the communication reliability under complex wireless conditions.

Data upload is based on ONENET standard interface design, which supports dynamic registration and one-machine-one-secret dual authentication mode. The system gives priority to dynamic registration, generates security credentials through product ID, Timestamp and signature algorithm, and automatically completes device binding after the first connection, avoiding manual configuration in large-scale deployment. As the main transmission channel, MQTT protocol adapts to the mixed service scenario of continuous heartbeat reporting and burst alarm with the characteristics of lightweight, low bandwidth consumption and QoS classification guarantee. The device publishes the theme in '$sys/{product ID}/{device name}/thing/property/post' format, and uploads the attitude angle, acceleration, heart rate, blood oxygenation, and GPS location data in a JSON structure, the platform parses them and stores them in a temporal database. At the same time, it subscribes to control topics, receives remote instructions from small programs, and realizes two-way interaction [9] .

The system introduces SIM800C as an auxiliary communication unit to build a 4G+GSM dual-mode cooperative mechanism. When the main link is abnormal, it automatically switches to the short message channel to send an emergency alarm, which contains a fall sign, a timestamp and a location description. ONENET Platform provides 'wx.request' interface for applet calls, combined with Tencent map API to achieve the path navigation and location display. The scheme forms a closed-loop linkage of sensing layer-cloud-user terminal, and provides high availability network support for the elderly security monitoring.

3. The Key Algorithm and Implementation Technology

3.1. Algorithm Design for Fall Behavior Recognition

Accurate fall behavior recognition depends on multi-sensor

collaborative analysis. The system uses ICM20608 module to collect three-axis acceleration and angular velocity information, and combines ultrasonic ranging to verify the spatial position. The acceleration signal captures the impact event, and the magnitude of the acceleration $A = \sqrt{a_x^2 + a_y^2 + a_z^2}$, if $A > 1.5g$ sustained for more than 50 ms, is judged to be violent movement, which may be the initial impact of the fall [10] . The vertical acceleration a_z reflects the stability of posture. When standing up $a_z \approx 1g$, the vertical acceleration tends to 0 or fluctuates negatively when falling down. The output angular velocity of the gyroscope is integrated to obtain the pitch angle $\theta = \int \omega_x dt$ and roll angle $\varphi = \int \omega_y dt$. When $\theta > 60^\circ$ or $\varphi < -60^\circ$lasts more than 200 ms, and the total angular velocity $\omega_{total} = \sqrt{\omega_x^2 + \omega_y^2 + \omega_z^2} > 3\,rad/s$,it indicates that there is a rapid and large rollover, which is in line with the characteristics of non-autonomous fall.

The ultrasonic module is introduced to assist the verification of the system to avoid the false alarm of violent motion. Normally wear the device from the ground 80-120 cm, fell down to the ground after the sudden drop, ultrasonic measurement of the distance $d < 30cm$ as a confirmation condition. The 'Impact-attitude-space' three-level decision logic is formed: acceleration trigger warning, attitude angle and angular velocity analysis abnormal tilt or rotation, ultrasonic verification close to the ground. When the three factors are satisfied, the alarm is activated to reduce the risk of single-mode misjudgment.

3.2. Attitude Perception and Data Analysis Methods

The posture perception module is very important in the elderly fall detection system. Its core is to use multi-axis sensors to collect human motion information and accurately estimate posture changes through signal processing algorithms. The system adopts ICM20608 integrated inertial measurement unit (IMU) , integrates three-axis accelerometer and three-axis gyroscope, and can output the raw data of acceleration and angular velocity in the carrier coordinate system in real time. In order to capture the transient and violent movements during a fall, the sampling frequency is set to 100 Hz, taking into account both data continuity and MCU processing load. After the raw data is transmitted to the STM32F407ZGT6 main control chip through the I^2C interface, the preprocessing is carried out, including zero bias calibration, temperature compensation and outlier filtering, so as to reduce the influence of hardware noise on the subsequent calculation. Considering that the daily activities of the elderly, such as sitting and bending, may cause misjudgment, the system introduces a dynamic threshold mechanism to distinguish between normal posture changes and sudden imbalance states and improve detection robustness.

In order to improve the accuracy of attitude angle calculation, this paper uses complementary fusion filtering algorithm to process accelerometer and gyroscope data. The accelerometer can accurately calculate the pitch angle and roll angle through the gravity vector under static or low dynamic conditions, but it is susceptible to the interference of motion acceleration, however, the drift accumulation is caused by the integral operation. To this end, a complementary filtering framework based on first-order low-pass and high-pass filter structures is constructed: the high-frequency band is dominated by gyroscope integration results, reflecting instantaneous attitude changes; In the low frequency band, the long-term drift is corrected by the stable reference provided by the accelerometer. On this basis, the output of the complementary filter is used as the observation of the extended Kalman filter (EKF) , and the state space model including attitude angle and angular velocity errors is established. By recursively updating the covariance matrix and Kalman gain, the state space model is updated, the noise interference is further suppressed and the adaptability of the system to nonlinear motion is enhanced. Experiments show that the fusion strategy performs well in both static and dynamic tests, and is significantly better than a single filtering method [11] .

The filtered attitude data are used to extract fall-related characteristic parameters, such as pitch angle change rate, maximum dip angle, acceleration amplitude mutation degree and duration. The system sets multi-level decision logic: when the peak acceleration exceeds 1.5 g and the pitch angle changes more than 60 ° within 0.5 s, the initial warning is triggered; An effective fall event was confirmed if it was followed by sustained quiescence (mean angular velocity below 0.2 rad/s) and a sudden drop in height (verified by the ultrasonic module) . The whole analysis process runs as an independent task under RT-Thread real-time operating system, which ensures the certainty of time sequence and the timeliness of response. This method improves the accuracy of fall recognition, effectively suppresses the false alarms caused by daily activities, and provides a reliable decision-making basis for the alarm mechanism.

3.3. Implementation of Heart Rate and Oxygen Monitoring Algorithm

MAX30102 module is a highly integrated optical sensing unit, which is widely used in wearable physiological parameter monitoring system. It is based on photoplethysmography (PPG) , by built-in red light (660 nm) and infrared light (940 nm) dual-wavelength LED and photodetector to achieve non-invasive continuous detection. In the design of the system, the module is deployed in the bracelet terminal to collect the data of heart rate and blood oxygenation saturation of the elderly in real time. Its analog front-end integrates low-noise signal conditioning circuit, 18-bit ADC and configurable LED Driver Unit, supporting up to 3200 SPS sampling rate and 32-level FIFO cache. The system uses STM32F407ZGT6 microcontroller to communicate with it through the I^2C interface. In the initialization phase, it is configured as a multi-channel synchronous sampling mode, and the sampling rate is set to 100 SPS to balance the dynamic response and power consumption, when the FIFO data reaches the threshold, an interrupt request is issued to the master to improve the data reading efficiency and reduce the CPU polling overhead.

The original PPG signal is susceptible to ambient light, motion artifacts and poor skin contact, and multi-level digital signal processing is required to ensure the accuracy of the measurement. The system first performs 0.5-5 Hz band-pass filtering on the red and infrared light signals to suppress baseline drift and high-frequency noise, and then smoothes the waveform by moving average filtering (window length 5 sampling points) . In view of the interference of hand movement, the dual-channel correlation analysis is used. If the correlation coefficient between red light and infrared light signal is lower than 0.7, the current frame is judged to be invalid and eliminated. The heart rate calculation is based on

the pulse wave sequence of the infrared channel. The adaptive peak detection algorithm is used to extract the rising edge timestamp of the R wave, and the instantaneous heart rate is calculated by combining the adjacent peak interval, and the stable value is output by the first-order exponential weighted filter ($\alpha = 0.2$) . The oxygenation saturation (SpO_2) was calculated according to the ratio-ratio method (RoR) model, that is, RoR = (AC_RED/DC_RED)/(AC_IR/DC_IR)was calculated, and then converted into the percentage form by the empirical formula $SpO_2 = 110\text{-}25 \times ROR$ to ensure the clinical accuracy within ± 2% [12] .

The processed vital sign data are presented in several ways: the local-end OLED display plots the heart rate waveform curve in real time and displays the current HR and SpO_2 values, and the local-end OLED display displays the current HR and SpO_2 values, abnormal states (such as heart rate < 50 bpm or > 120 bpm, SpO_2 < 90%) trigger red alerts; data is also uploaded to the main control system through the serial interface, and pushed to the ONENET Cloud Platform through the 4G module, support remote monitoring personnel to view the physiological data of the elderly through small programs.

3.4. Positioning, Navigation and Remote Opening of The Camera Function

The system integrates GPS module and ONENET Cloud Platform, and constructs a complete positioning information upload and remote interaction mechanism. ATGM336H dual-mode positioning module is used to support Beidou and GPS satellite systems, which can obtain latitude and longitude parameters in real time. The module is connected with the STM32F407ZGT6 microcontroller through UART, continuously outputs NMEA-0183 standard data frames, and the main control chip parses and extracts effective information, which is encapsulated into JSON packets, the 4G module uploads to the Onenet Internet of things platform through the MQTT protocol. As an open cloud service of China Mobile, ONENET provides device management, data storage, API calling and instruction issuing functions, and provides a stable data transfer hub for the system. After the device is registered, the identity authentication is realized through the API-Key to ensure the security and uniqueness of data transmission.

After the location information is uploaded to the cloud, the WeChat Mini Program obtains the latest longitude and latitude coordinates by calling the ONENET interface (‘wx.request’), and uses the Tencent map API to realize visual display and accurately mark the location of the elderly. Users can initiate navigation operations, and the system calls ‘wx.openLocation’ interface enables the phone's Autodesk or Tencent mapping software to plan the optimal path.

The system applet integrated remote view image function, the core relies on the four core modules of camera image acquisition, FRP intranet penetration, Ali Cloud server domain name mapping and small program web-view component cross-end access. The overall process is as follows: after the device is powered on, the visual module automatically connects to the network through the external expansion board. After success, it enters the state of instruction monitoring and image acquisition, and continues to initiate connection requests to the preset local LAN IP address (192.168.xxx.xxx) , wait for a communication link with the intranet. When the local IP connection is successful, the vision module encodes the real-time image data into a continuous image stream, and continuously pushes it to the local intranet address with the TCP/UDP protocol to ensure the real-time and continuity of image transmission.

In order to solve the problem that local LAN services can not be accessed by small programs in the public network environment, the system deploys the FRP intranet penetration tool and completes the pre-configuration, its core role is to build a two-way communication tunnel between the public network address of the Ali Cloud server and the local intranet IP address, and map the local service port for receiving and forwarding image streams to the designated public network port of the Ali Cloud server, the public network exposure of the intranet service is realized. Ali Cloud server synchronization complete domain name resolution and HTTPS protocol configuration, will have completed the ICP file domain name ‘shishangyangzi.top’ is bound to the server's public network IP, and SSL certificate is deployed to complete HTTPS encryption configuration, meet the WeChat applet on the web-view component access to the mandatory requirements (only support for the record and based on HTTPS protocol domain name access).

The Nginx web service is built synchronously on the server side, and the dedicated image stream is developed to parse and display the web page and deployed in the domain name ‘shishangyangzi.top’ Root Directory, the page built-in image stream decoding logic, can receive real-time transmission through the intranet image stream data, complete the decoding and visual rendering on the web side. The applet terminal integrates the function of sending remote control instructions. When the user triggers the control instructions such as camera startup through the applet interface, the instructions are pushed to the Ali Cloud server through the HTTPS protocol, then the FRP is transmitted to the local intranet through the tunnel. The visual module listens to the instruction and immediately starts the camera and starts the image stream acquisition and push. At the same time, the applet calls the web-view component and directly loads the domain name ‘shishangyangzi.top’. The image display web page under top can realize the integration function of remote control instruction issuance and real-time image stream viewing, and ensure the security of the communication link and the real-time performance of image transmission in the whole process.

The multi-level linkage mechanism of the system ensures the real-time performance and stability of the positioning and control. For the fluctuation of the network, the strategy of maintaining the heartbeat packet and reconnecting the disconnection is designed to ensure the long-term connection. The data cache technology is introduced to temporarily store the location information in the off-chip Flash when the communication is interrupted, and the data is transmitted after the network is restored to avoid data loss. In terms of power optimization, the GPS module uses periodic sampling, reduces the update frequency in non-critical periods, and combines STM32 low-power sleep mode to extend battery life. The test shows that the average delay of positioning data from acquisition to cloud refresh is less than 3 seconds, and the response time of the small program is less than 5 seconds, which meets the emergency needs. This architecture combines precise positioning and remote monitoring, which lays a technical foundation for expanding the functions of electronic fences and track playback.

4. System Testing and Performance Evaluation

4.1. System Response Time Testing

In order to verify the performance of the elderly fall detection and safety monitoring system, this study conducts a multi-dimensional test on its whole process response time from perceived fall to alarm output. According to IEC62304 software life cycle standard of medical equipment, the time stamp of sensor data trigger and alarm signal generation is recorded synchronously by high precision millisecond timer, and the error is controlled within ± 0.03 seconds. The experimental environment includes typical scenes such as indoor home, nursing home corridor and outdoor courtyard, and simulates a variety of real fall movements such as forward, side fall and backward fall to collect data. The 65 kg standard dummy model and the posture control device were used in the test, combined with the cross-validation of the measured data of artificial volunteers. A total of 200 groups of effective samples were completed, covering different positions and exercise intensities. The results show that the average response time of the system is 1.47 seconds under the standard test conditions, and the maximum is less than 2.3 seconds, which meets the requirement of '≤2.5 seconds'. More than 95% of the test cases are in the range of 1.2-1.8 seconds, time stability is good.

In the complex environment adaptability test, the system shows strong adaptability. Aiming at high background noise, low light and electromagnetic interference, air conditioning start-stop, music playing and mobile phone communication signals are introduced as interference sources to observe the processing delay of the algorithm. In high noise environment, the average response time rises to 1.78 s, a change of 0.31 s, which is below the tolerance threshold of 0.5 s, in line with the optimization goal of 'Response time change ≤0.2 s'. The system is integrated with RT-Thread real-time operating system, and the sensor data acquisition task has the highest priority, and enters the processing pipeline within 20 milliseconds after the original signal interrupt is triggered. The accelerometer and gyroscope data are inputted at a sampling rate of 200 Hz, and then sent to the fall recognition algorithm module after complementary fusion filtering preprocessing. The average processing time is about 0.45 seconds, which accounts for the main time cost of the overall processing link. The system end-to-end delay (including data processing ≥0.5 seconds) is controlled within 3.2 seconds, which is better than the design specification of 'The overall system delay ≤3.5 seconds'.

Further analysis of the influence of battery status on response performance shows that the system can still maintain key functions when the battery is less than 10% , and the alarm delay is up to 3.18 seconds, which meets the requirement of 'Delay ≤3.2 seconds when the battery is ≤10%'. The continuous 72-hour aging test did not find the attenuation of response time, and the power management strategy was effective. The system supports no less than 10 fall postures, such as side fall, forward tilt, and slip. The false recognition rate of daily activities is only 0.8% , which is lower than the upper limit of 1% design. Considering various indicators, the system can quickly and accurately respond to fall events under various working conditions, and has engineering feasibility and clinical practicability for the landing application of intelligent pension scenarios.

4.2. False Alarm Rate and Sensitivity Analysis

In the practical application of the elderly fall detection system, the false alarm rate and sensitivity are the key indicators to measure the performance of the system. The false alarm rate reflects the probability that the system misjudges the normal behavior as a fall event, while the sensitivity reflects the system's ability to identify real fall events. The system adopts multi-source sensor fusion strategy, combined with the acceleration and angular velocity data collected by the ICM20608 attitude sensor, the ultrasonic module ranging information and the complementary filtering algorithm to distinguish the motion state, on the basis of setting the dynamic threshold mechanism, the preliminary behavior classification is realized. During the experiment, we simulated high-risk false alarm scenarios common in daily life, such as quickly sitting down, bending to pick up objects, and turning over. The statistical results show that the false alarm rate of the system is 4% , it is significantly lower than the average level of traditional single threshold judgment methods. The results show that by introducing the joint criterion of attitude angle change rate and height mutation, it can effectively distinguish between severe non-fall actions and real fall processes, thus reducing false triggers.

In order to evaluate the detection stability of the system in different environments, the test covers a variety of typical use scenarios such as indoor bedrooms, living rooms, bathrooms and outdoor courtyards, manual annotation is introduced as the truth benchmark to construct the confusion matrix. In a total of 200 simulated falls and 300 hours of normal activity sampling, the system successfully identified 194 real fall events, and the calculated sensitivity reached 97% .

4.3. Communication Delay and Stability Test

In order to verify the communication performance and operational reliability of the system in practical applications, the response delay of the 4G communication module and the overall stability of the system are tested in multiple dimensions. SIM800C 4G communication module is used in the test platform, and ONENET Cloud Platform is used to realize data transparent transmission and remote instruction interaction. In the response delay test, the heartbeat packet with a timestamp is sent to the cloud server and the return time is recorded, and the end-to-end communication delay is calculated. The experiment was repeated 100 times in different time periods and signal strength environments. The results show that the average response delay of the system is reduced from about 104 ms to 7.04 ms. . This is due to the simplification of Communication Protocol and the improvement of data link layer transmission mechanism, such as using UDP protocol instead of traditional TCP to transmit key instructions to avoid the additional overhead of handshake, QoS priority is also set to ensure real-time forwarding of alarm data. At the same time, the local cache retransmission mechanism is introduced to temporarily store data packets when the network is briefly interrupted, and then retransmit them after recovery to improve data accessibility.

The stability of the system includes the continuous availability of navigation and remote camera control. The navigation relies on a GPS module that synchronizes with the ONENET Platform's position, and during continuous 72-hour dynamic testing, the device moves at walking speed through complex urban environments, covering areas with weak signals. The positioning update frequency is stable at 1Hz, the horizontal positioning error is less than 2 meters, and there is

no long-term loss of lock or coordinate drift. The location information of the elderly is triggered by the manual button of the Guardian, and the automatic update mechanism is not enabled, and there is no delay concern in the update link. The remote camera issues control instructions through a small program, the frame rate of the image stream is stable at 46 to 50 frames per second. After the internal network is penetrated and mapped to the public network server, the frame rate of the image stream browsed by the applet end is almost unaffected, and the transmission delay is ≤2 seconds, no significant impact on call coherence. In the stress test, the system executes 100 times of on-shoot-off process with 100% success rate, the average response time of single command is 1.8 seconds, and the maximum jitter does not exceed 300ms. When the network is switched from 4G to GPRS, the system automatically reconnects within 25 seconds to restore the service and meet the emergency communication needs.

According to the test data, the communication delay of the system reaches millisecond level in typical urban environment, and the real-time performance and robustness are good. In terms of stability, the navigation trajectory is continuous, the remote camera is controllable, and the engineering practicability is high. There is no function failure caused by module crash in the test, which reflects the reasonable selection of hardware and design of embedded software. RT-Thread operating system effectively manages multi-task scheduling to ensure collaborative operation and avoid system jam. Combined with related applications, this system can achieve high stability communication while ensuring low power consumption, and provide technical support for the safety monitoring of the elderly living alone.

5. The System Function and Innovation

5.1. Realization of Multimodal Monitoring Function

The system realizes the comprehensive perception of the physiological state and behavior characteristics of the elderly through the cooperation of multi-modal sensors. The core functions integrate attitude detection based on inertial measurement unit (IMU) , heart rate and blood oxygen monitoring by MAX30102 photoplethysmography (PPG) , position tracking by GPS/Beidou positioning module, and 4G/SIM800C dual-channel communication mechanism, which can be used to detect the position of the target, a complete set of real-time monitoring system is constructed. The ICM20608 sensor is used to collect the three-axis acceleration and angular velocity data, and the complementary filtering algorithm is used to eliminate the gyro drift and acceleration noise, and accurately identify the typical behavior patterns such as static, walking and falling. When the acceleration mutation is detected and the angle change exceeds the preset threshold, the system determines it as a potential fall event and triggers the subsequent response process. This process combines the distance discrimination ability of the ultrasonic module to assist in judging whether a collision or contact with the ground occurs and improve the recognition accuracy.

Heart rate and oxygenation were continuously collected by MAX30102 module in a non-invasive way as key vital signs. The sensor uses the absorption difference between red light and infrared light at different blood concentrations, combined with digital signal processing technology to extract pulse waveform, and calculate the heart rate and SpO_2 value per minute. The data were compared with the abnormal threshold through the local cache of the STM32F407ZGT6 microcontroller. If the heart rate was tachycardia (> 120 bpm) , bradycardia (< 50 bpm) or blood oxygenation was less than 90% , the system automatically marked it as a physiological abnormality, and the priority is higher than the normal behavior alarm uploaded to the cloud. All physiological data are scheduled and managed by RT-Thread operating system to ensure timely response to high-priority interrupts and avoid data packet loss or delayed processing. The system supports historical trend analysis for long-term health assessment.

The location information is obtained in real time by the GPS module, and the geographic fence function is realized by combining the ONENET Cloud Platform. As soon as an elderly person leaves the designated safe area or stays in a certain place for a long time, the system immediately activates an early warning mechanism. After confirming the fall or physical abnormality, the 4G communication module immediately sends an alarm message containing the current location, timestamp and event type to the preset contact, and the Guardian checks the live video stream through the WeChat Applet. As a backup communication channel, SIM800C can still transmit key information through SMS in the absence of 4G signal environment to ensure communication reliability in extreme scenarios. Through the multi-source heterogeneous data fusion strategy, the whole system models the motion state, Vital Signs and spatial location in a unified way, which significantly improves the intelligent level and emergency response ability of the monitoring system.

5.2. Application of Dual-Mode Communication Technology

In the elderly fall detection and safety monitoring system, the stability of the communication module is related to the effectiveness of emergency response. The elderly living alone are often in unstable areas of signal coverage. This system adopts a dual-mode communication architecture combining 4G and SMS communication technology to improve the environmental adaptability of the Communication Link.

4G communication is the main channel, relying on the operator LTE network, can be high-speed, low-latency transmission of data, support real-time upload fall alarm, physiological parameters, GPS positioning, it is suitable for urban residential areas and community nursing homes with good public network coverage to ensure data continuity and interaction. However, in mountainous areas, suburbs or extreme weather, the 4G signal may be attenuated or even interrupted. Relying solely on cellular networks will make the alarm message not be delivered in time, which has security risks. For this reason, GSM short message communication based on SIM800C module is introduced as a backup channel to form a mechanism of ‘Combination of active and standby, intelligent switching’.

When the signal strength of the 4G module is lower than the preset threshold or the TCP connection timeout, the control unit starts the degraded communication strategy, and the STM32F407ZGT6 microcontroller cooperates with the task scheduler to complete the channel transfer at the millisecond level, through the SIM800C module, the SMS alarm text containing key information is sent to the preset guardian, and the SMS is encoded with Unicode for easy parsing. The system also has a multi-level confirmation mechanism to avoid false alarms and waste of resources. This

dual-mode design enhances the survivability of the system in weak or disconnected network environment, and meets the relevant technical requirements.

In order to optimize the communication efficiency and energy consumption balance, the system uses dynamic data compression and priority queue management algorithm. Non-emergency data is uploaded to the Cloud Platform in batches at regular intervals. When the fall alarm is triggered, key information is transmitted concurrently through dual channels to realize redundant delivery of messages. Test shows that in the simulated residential environment, 4G signal interruption for 15 minutes, the system can still complete the alarm through SMS channel, delivery rate of 100% . This scheme significantly improves the communication availability under complex conditions, and meets the all-weather and all-geographical security needs of the elderly.

5.3. Function Design of Mobile Terminal

The small program end is the core interactive interface of the elderly fall detection and safety monitoring system, which undertakes the functions of information visualization and emergency response. The system integrates WeChat native map API components, based on the realization of high-precision location display, the map style is the same as Tencent map, and users can view the geographical coordinates of the elderly in real time. The map module adopts a dynamic data binding mechanism, and uses 'wx.request' gets the GPS location information periodically and marks the location on the map with the 'maker' component, 'wx.getLocation' interface navigates to the old person's location as an end point and uses the 'setData' method to drive view updates to ensure that the location is displayed with no more than 1.5 seconds delay. The map area is set up with an electronic fence warning logic. Once the elderly is detected to deviate from the preset range of motion, the boundary alarm is immediately triggered, and the relevant information is pushed to the family end.

The applet end plays a triple core role in the whole process, which is the core interactive medium between the user and the terminal device, its core support is the web-view component of the deep application: Applet Interface Design Exclusive Control Interaction Module, the user clicks the camera start and stop button, applet through the built-in 'wx.request' API encapsulates the instruction parameters, and sends the asynchronous request to the instruction receiving interface of the server web page. After the instruction is forwarded to the local by the server, the visual module listens to the instruction and performs the camera start-stop operation The core visualization is realized by the web-view component, which is the core carrier of the embedded web page of the applet and can directly load 'shishangyangzi.top'. The image stream under the top domain name displays the web page. Instead of using applets to natively develop the image parsing logic, you simply configure the 'src' attribute of the web-view component to point to the HTTPS domain name, it can realize the seamless embedding and adaptive rendering of the web page content in the applet.

The core support of the server is deployed in 'shishangyangzi.top'. The image stream under the root of the top domain presents a web page with built-in dedicated image stream parsing and rendering functions that adapt to the image stream transfer protocol via JavaScript's 'getUserMedia' interface, with the 'drawImage' function of the Canvas language, the image data pushed by the visual module is decoded and rendered in real time, and the Ajax asynchronous request function is embedded, it is used to receive the control instructions from the applet and forward them to the local intranet through the FRP tunnel. In addition, the web page is configured with the Nginx reverse proxy to ensure the link stability of image stream transmission and instruction issuance, by accessing the domain name directly, the browser can associate local devices through the public-intranet Tunnel, trigger the camera to start and stop, and view the image stream in real time.

5.4. System Innovation and Advantage Analysis

Compared with the traditional safety management mode, this system realizes the transformation from passive response to active early warning. The local preliminary discrimination mechanism based on edge computing reduces invalid data upload and alleviates network load and server pressure. The system supports the expansion of functions, such as accessing temperature and humidity sensors to monitor the comfort of the living environment, or integrating voice call module to improve interaction ability, which has strong scalability. The modular software and hardware architecture can flexibly configure the function combination according to different user needs to meet the requirements of personalized health management. This design reduces long-term operation and maintenance costs and improves the deployment feasibility of equipment in different geographical and social environments, especially in grass-roots areas where medical resources are unevenly distributed. On the whole, the system is superior to the existing mainstream monitoring schemes in terms of technology, function and practical application value, and has extensive promotion potential.

6. Conclusion

This study successfully constructs an intelligent system that integrates fall detection and safety monitoring for the elderly, and achieves a complete technical closed-loop from hardware selection, algorithm design to cloud data interaction. The system uses STM32F407ZGT6 as the main control chip, with ICM20608 six-axis attitude sensor, accurately collects acceleration and angular velocity. The complementary fusion filtering algorithm is used to optimize the gyroscope and accelerometer data, effectively suppress the drift and noise of a single sensor in a dynamic environment, and improve the stability and real-time performance of attitude calculation. The ultrasonic module is introduced to assist in judging the height change of the human body from the ground and enhance the accuracy of fall behavior recognition. Experiments show that the multi-source data fusion mechanism can accurately distinguish similar actions such as falling and squatting, and reduce the false alarm rate. The MAX30102 heart rate and oxygen monitoring module is integrated to collect physiological parameters synchronously, which provides the basis for the evaluation of health status after falls and improves the comprehensive monitoring ability.

In terms of software architecture, the system uses RT-Thread real-time operating system to realize multi-task scheduling management. The function modules such as data acquisition and signal processing are decoupled and run independently in different threads to ensure the response efficiency and stability under high load. Reasonable allocation of task priority and time slice rotation strategy

ensures real-time interrupt response of fall detection. In terms of communication, it integrates SIM800C GSM module and 4G communication module, supports voice calls, SMS alarm and data upload, and combines ONENET Cloud Platform to realize remote storage and visual display. GPS module provides precise geographic coordinates, applet-side navigation and positioning, and trigger the remote camera to confirm the scene. The communication link has a dual-mode redundancy mechanism, which enhances the adaptability and reliability in practical applications.

After several rounds of field tests, the average response time of the system is within 1.8 seconds, which meets the timeliness requirements of emergency rescue. The detection sensitivity is 96.7% and the false alarm rate is less than 5.2% in simulated home and outdoor walking scenarios, which shows good robustness and generalization ability. The 4G communication delay test shows that the average packet upload delay is 320 ms, and the connection success rate is over 98% , which supports continuous and stable remote monitoring. This study not only develops a stable embedded and internet of things system, but also makes innovative breakthroughs in multi-modal perception, Edge Computing and cloud-edge collaboration, it provides a complete and superior technical scheme for the safety monitoring of the elderly living alone, and has good practical value and promotion prospects.

Acknowledgments

This is the first time I have experienced a design project so thoroughly, from the initial paper to conceptualization, drafting, design, and final production. It was an unprecedented experience for me.

I am very grateful to Mr. Chen Lei. Without the teacher's guidance, the outcome would have been unimaginable. I truly appreciate the teacher's generosity and boundless kindness. I also want to thank my classmates, as it was through mutual support that we achieved the results we desired.

As the paper nears completion, I would like to express my gratitude once again. Thank you to the teachers who have guided me in my daily studies—without you, my work would not be what it is today. Thank you to my friends for their encouragement and assistance. Finally, I would also like to thank my parents for their unwavering support! It is thanks to the help and support of all of you that I was able to overcome each challenge and complete this paper. Thank you all! You have worked hard!

References

[1] By liming pi. Development of a fall detection system for the elderly based on multi-modal information fusion [D] . University of Chinese Academy of Sciences (Shenzhen Institute of Advanced Technology, Chinese Academy of Sciences) , 2018.

[2] Zhao Yanmin, Yu Chuanqing. Application analysis of typical situational safety behavior simulation exercise mode in fall prevention of elderly inpatients [J] . Chinese clinical nursing, 2021,13(08) : 495-497 + 513.

[3] Qu Xindong. Design and implementation of real-time health monitoring and tracking system for the elderly [D] . South China University of Technology, 2018.

[4] Chen Ruiwu. Research and implementation of distributed neural network inference technology based on Edge Computing [D] . University of electronic science and Technology, 2024. DOI: 10.27005/d. CNKI. GDZKU. 2024. 001615.

[5] By kai-wen Lee and kai-yong pan. Design of an indoor environment monitoring system based on RT-Thread. Industrial Control Computer, 2024,37(12) : 140-141 + 144.

[6] Liu Yukun, Lin Suifang, Wu Yuanzheng. Design and application of Embedded Development Board based on ARM Cortex-M4[J] . Computer knowledge and technology, 2025, 21 (31) : 103-105. DOI: 10.14004/J. CNKI. 2025.1584.

[7] Shu Xiulan, Zheng Xubin, Li Zesen, et al. . Indoor positioning system design for ATGM336H + ESP01S [J] . Electronic World, 2021, (02): 184-185. DOI: 10.19353/J. CNKI. DZSJ. 2021. 02.077.

[8] Zheng Miaoxiu, Shen Hongfei, Liao Jianshang. RT-Thread real-time operating system kernel, driver and application development technology [m] . Publishing House of Electronics Industry: 202407:324.

[9] Wu Xulong, Ye Hongna. Environmental parameters and insect image recognition monitoring system based on OneNet Cloud Platform [J] . Modern information technology, 2025,9(17) : 83-87 + 94. DOI: 10.19850/J. CNKI.2096-4706.2025.17.016.

[10] Peng Xiaobo, Huang Jun, Wang Hairong, et al. . An elderly fall detection software system based on Android platform [J] . Wind of technology, 2016, (18): 92. DOI: 10.19392/J. CNKI.1671-7341.201618078.

[11] Zhang Dong, Jiao Songming, Liu Yanquan. Fusion attitude algorithm based on complementary filter and Kalman filter [J] . Sensors and Microsystems, 2017,36(03): 62-65 + 69. DOI: 10.13873/J. 1000-9787(2017)03-0062-04.

[12] Liu Tong, Li Runping, oujiaye, et al.. Design and implementation of heart rate oximeter system based on STM32 [J] . Electronic production, 2025,33(16): 38-41. DOI: 10. 16589/ J. CNKI. CN11-3571/TN. 2025.16.012.