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Original Research Article

Design and implementation of a multimodal health monitoring system for elderly living alone based on STM32

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Abstract: With the rapid growth of the aging population, ensuring the health and safety of elderly people living alone has become increasingly important. This paper presents the design and implementation of an embedded health monitoring system based on the STM32F103C8T6 microcontroller. The system integrates a DS18B20 temperature sensor, a MAX30102 heart rate and blood oxygen sensor, an MPU6050 inertial sensor, a GPS positioning module, an OLED display, and an ESP32 wireless communication module, enabling real-time acquisition of physiological parameters, motion status, and location information. Alarm thresholds can be configured locally or remotely via a mobile application. When abnormal physiological conditions or fall events are detected, the system triggers alarm notifications and uploads data to a cloud platform for remote monitoring. Experimental results show that the proposed system provides stable wireless communication, reliable data acquisition, and effective abnormal event detection, demonstrating its feasibility and practicality for elderly health monitoring applications.

Keywords: elderly living alone; health monitoring; fall detection; STM32; IoT

1. Introduction

With the rapid development of Internet of Things (IoT) and smart home technologies, the health and safety of elderly people living alone have attracted increasing attention.According to reports from Xinhua News Agency, by the end of 2023, the population aged 60 years and above reached 297 million, accounting for 21.1% of the total population [1]. Elderly individuals living alone face higher risks during emergency health events due to the lack of timely assistance.

Currently, various microcontroller-based health monitoring and fall detection systems have been reported. Some studies focus on accelerometer-based fall detection, while others monitor vital signs such as heart rate and blood oxygen saturation[2,3,6,7]. However, these systems often suffer from limited functionality, insufficient real-time performance, or inadequate remote management capabilities. Although machine learning and vision-based approaches have been explored, their implementation remains challenging for resource-constrained embedded systems[8,14].

To address these limitations, this paper presents a multi-sensor health monitoring system for elderly people living alone.The system integrates physiological monitoring, motion and posture analysis, and real-time positioning. Health data are transmitted to a cloud platform via an ESP32 wireless communication module, enabling remote access, threshold configuration, and timely alarm notifications through a mobile application. The system also supports local alarms and GPS-based positioning, providing effective technical support for emergency response and elderly health care[11,15].

2. Relevant technologies

2.1. FreeRTOS

FreeRTOS is a widely used real-time operating system for embedded microcontrollers, supporting architectures such as ARM Cortex-M. It provides task priority scheduling, task synchronization, interrupt handling, and time-slicing mechanisms, enabling real-time and deterministic system responses in resource-constrained environments.With its low memory footprint and lightweight kernel,FreeRTOS is particularly suitable for deployment in Internet of Things (IoT) devices[3].

2.2. MQTT

MQTT is a lightweight publish/subscribe messaging protocol built on top of TCP/IP, making it well suited for Internet of Things (IoT) devices with limited bandwidth and constrained resources. Devices can publish or subscribe to topics through an MQTT broker, enabling asynchronous communication between devices and cloud platforms. The protocol features low overhead, reliable message delivery, and the ability to maintain long-term connections in unstable network environments[6].

2.3. Sensor technology

The system integrates multiple sensing and positioning modules to enable comprehensive monitoring of the health and safety of elderly individuals living alone. The MAX30102 sensor is used to measure heart rate and blood oxygen saturation based on photoplethysmography (PPG) and communicates with the MCU via an I²C interface.An MPU6050 accelerometer and gyroscope is employed to monitor motion and posture changes for fall and abnormal activity detection. Body temperature is measured using a DS18B20 digital temperature sensor with a 1-Wire interface. In addition, a GPS module provides real-time location information by parsing NMEA data via a serial interface. By fusing physiological, motion, and location data, the system achieves reliable and real-time health and safety monitoring for elderly individuals living alone [6,7,12].

2.4. Cloud platform and app architecture

The system reports sensor data to the cloud server via MQTT. The cloud platform is responsible for storing and analyzing this data, and provides APIs to the App side. The mobile App can view the elderly's physiological data, location information, and alarm events in real time. The App also supports remote setting of alarm thresholds and synchronizes these settings back to the device[11,13].

3. System architecture design

3.1. Overall architecture

The system adopts a layered architecture consisting of three main components: the terminal device, the communication module, and the cloud platform with a mobile application. The terminal device serves as the core unit for sensing and control, responsible for acquiring body temperature, heart rate and blood oxygen saturation, motion status, and location information of the elderly, as well as providing local display and preliminary alarm functions. The communication layer establishes a wireless connection with the cloud via an ESP32 module, enabling data upload and remote interaction. The cloud platform is responsible for centralized data storage and analysis, and it delivers health status information and alarm notifications

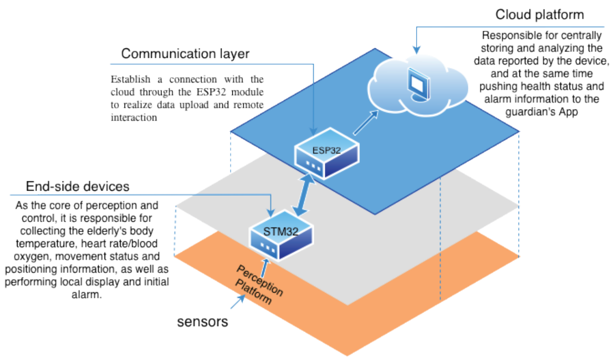

Figure 1. Overall architecture diagram.

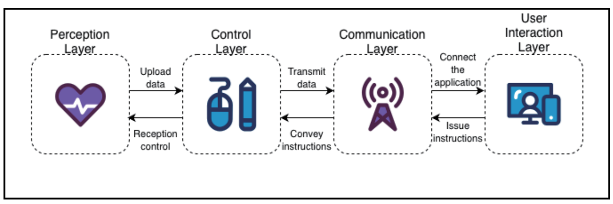

Figure 2. System design schematic diagram.

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to caregivers through the mobile application.

3.2. Module division

The system is organized into four functional layers:

Perception layer: Sensors for body temperature, PPG, acceleration/gyroscope, and GPS are used to acquire physiological and motion data and are interfaced with the STM32.

Control layer: The STM32 microcontroller performs data acquisition, filtering, calibration, threshold evaluation, and manages local display and alarm functions.

Communication layer: An ESP32 wireless module uploads processed data to the cloud via the MQTT protocol and receives remote configuration commands.

User interaction layer: The cloud platform and mobile application provide data storage, analysis, alarm notifications, and real-time monitoring for caregivers.

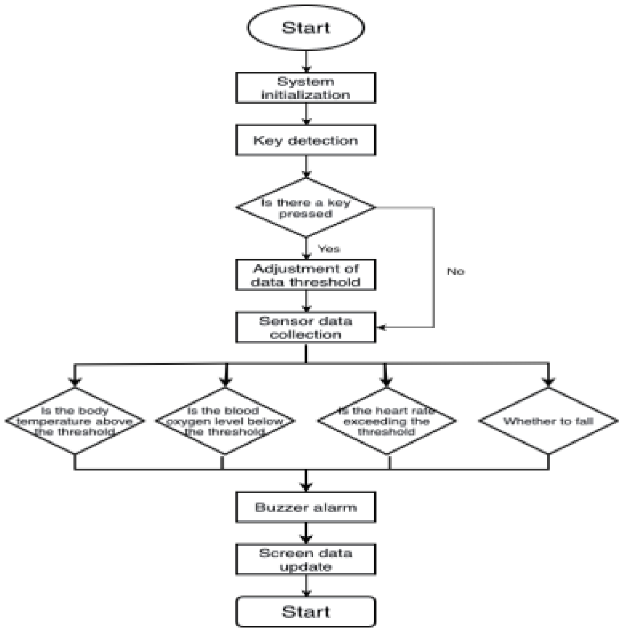

Figure 3. Workflow diagram.

3.3. Data flow and workflow

The data processing workflow begins with the terminal device periodically collecting raw data from the sensors. The STM32 microcontroller then performs preprocessing, including filtering and calibration, to reduce noise and correct measurement deviations, followed by threshold-based evaluation. When any physiological parameter or motion state exceeds the predefined safety limits, it is identified as an abnormal condition. The system immediately triggers a local alarm and uploads the abnormal event together with the associated data to the cloud platform via the communication module . After receiving the data, the cloud platform conducts further analysis and sends alarm notifications to caregivers through the mobile application, while storing the data and event records in a historical database for subsequent review and tracking[11,16].

4. Hardware design

The hardware design consists of six main components:

(1) STM32 control unit: An STM32F103C8T6 is used as the core controller for sensor data acquisition, processing, and local decision-making.

(2) Sensor modules: A DS18B20 digital temperature sensor, a MAX30102 heart rate and SpO_2sensor based on PPG technology, and an MPU6050 accelerometer and gyroscope for motion and fall detection.

(3) Positioning module: A GPS module communicates with the STM32 via UART to obtain real-time location information.

(4) Display module: A 0.96-inch OLED display connected through I^2C is used to show physiological data, motion status, location, and alarm information.

(5) Communication module: An ESP32 wireless module provides Wi-Fi connectivity and uses the MQTT protocol to upload health data and alarm events to the cloud.

(6) Power supply and human–machine interface: The system operates at 3.3 V, with optional battery support, and physical buttons are used for alarm threshold configuration[6,15,20].

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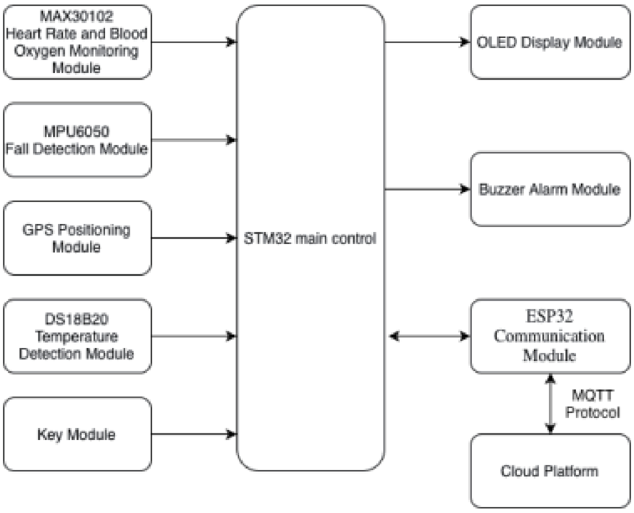

Figure 4. Hardware architecture diagram.

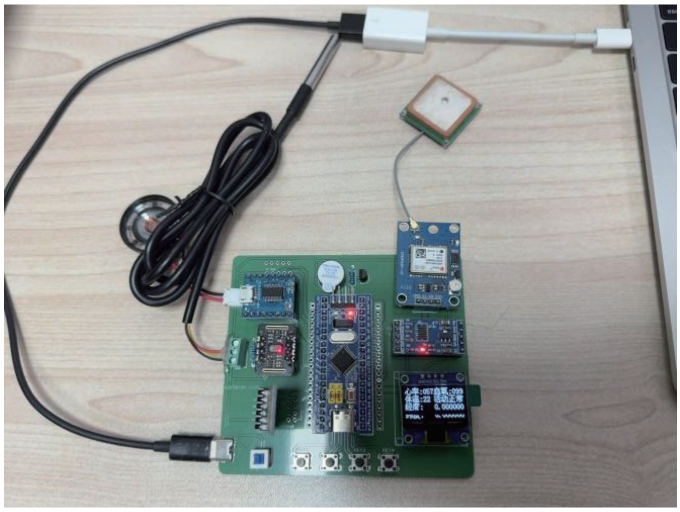

Figure 5. Physical diagram of hardware.

5. Software design and implementation

5.1. Sensor data collection task

In the software design of the system, the sensor data acquisition task is executed periodically by the STM32 microcontroller under either a FreeRTOS-based scheduling mechanism or a bare-metal loop. Raw data from various sensors are first collected through I²C and 1-Wire interfaces. The acquired data are then processed by filtering and calibration to suppress measurement noise and correct system deviations. Finally, the processed data are buffered in memory or queues to support subsequent threshold evaluation, alarm triggering, and data transmission.

5.2. Threshold judgment and alarm logic

The system incorporates a threshold-based decision and alarm logic module to continuously monitor physiological parameters and motion states for abnormalities. Users can configure alarm thresholds via physical buttons or a mobile application, and the STM32 microcontroller stores these parameters in non-volatile memory. During operation, the STM32 periodically reads the buffered sensor data and compares them with the predefined thresholds. When any parameter exceeds the safety limits or when motion impact surpasses the specified level, the condition is automatically identified as abnormal. The system then immediately triggers a local alarm and stores the corresponding abnormal event in a local queue for subsequent data upload and record keeping [7,10].

5.3. Communication subsystem

The system establishes serial communication between the STM32 and the ESP32 module to enable Wi-Fi connectivity. The device employs the MQTT protocol to upload processed vital sign data and alarm events to the cloud server, while also receiving threshold configurations and control commands from the cloud. Communication tasks are managed using a task/queue mechanism to ensure stable and reliable data transmission. The cloud platform provides centralized data storage and management, and the mobile application offers real-time data visualization, historical record queries, and alarm notifications for caregivers, thereby enabling remote monitoring and management[8,11].

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6. Experiment and result analysis

To evaluate the measurement accuracy of the proposed system, body temperature, heart rate, and oxygen saturation (SpO_2) were measured under three different conditions: resting, post-exercise, and calm states, and compared with standard medical reference devices.

As illustrated in Fig. 6, the average deviation of body temperature measurements was –0.21 °C, with a maximum deviation of ±0.35 °C. The heart rate measurements exhibited a mean deviation of –2 bpm, and the maximum deviation did not exceed ±4 bpm. For SpO_2, the average deviation was –1.5%, with a maximum deviation of ±2.3%.

Furthermore, the box plots shown in Fig. 7 indicate that the measurement deviations are narrowly distributed with limited outliers, demonstrating good stability and consistency of the proposed system across different physiological states. These results confirm that the system meets the accuracy requirements for daily health monitoring applications in smart healthcare environments[3,7].

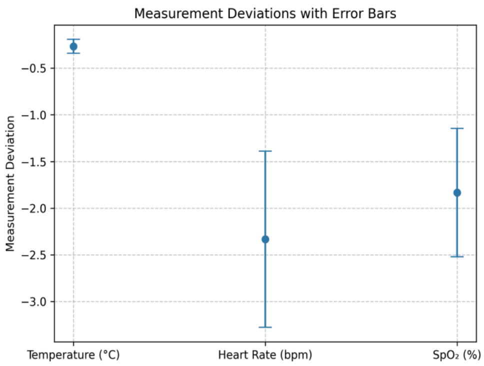

Figure 6. Error bar plot.

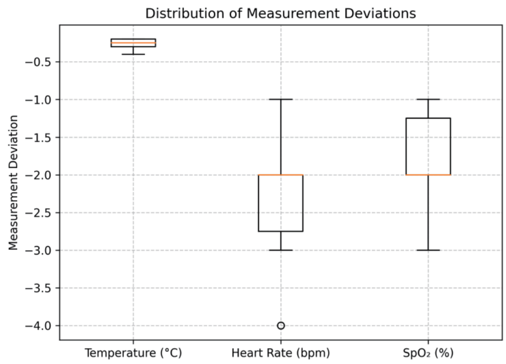

Figure 7. Box plot.

In the fall detection evaluation, a total of 80 fall events and 200 non-fall activities were conducted. The proposed MPU6050-based threshold algorithm correctly detected 78 out of 80 actual fall events, resulting in a miss detection rate of 2.5%. Among the non-fall actions, 8 instances were falsely classified as falls, corresponding to a false alarm rate of 4%. The resulting confusion matrix yields an overall accuracy of 96.43%, a sensitivity (recall) of 97.5%, and a precision of 90.7%. These results indicate that the system exhibits high sensitivity while maintaining a low false alarm rate, demonstrating its practical reliability for real-world fall detection applications[2,8,14].

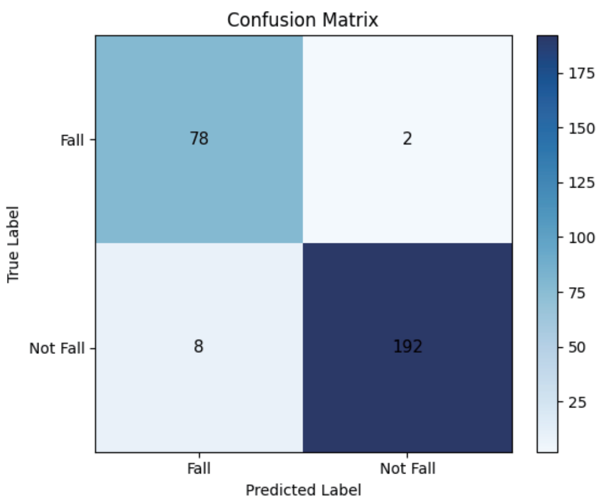

Figure 8. Confusion matrix of the proposed fall detection system.

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Outdoor GPS tests were conducted in an open area and compared with predefined reference points. The system achieved an average positioning error below 5 m, with a maximum error of less than 8 m.

For communication performance, the end-to-end latency from abnormal event detection on the STM32 to alarm reception at the cloud server was measured. The average delay was approximately 1.1 s, while the maximum delay did not exceed 2.2 s.

WiFi communication reliability was evaluated over 1000 consecutive upload cycles, resulting in a success rate of 99.6%.

Finally, in the cloud platform and mobile application visualization tests, the system successfully recorded all uploaded sensor data and alarm events. The mobile application enabled real-time data visualization, historical trend analysis, and alarm record querying and exporting. During the testing process, the user interface remained responsive, with no noticeable latency or performance degradation.

Overall, the experimental results based on the simulated datasets demonstrate that the proposed system exhibits stable and reliable performance in vital sign monitoring, fall detection, positioning, and data transmission under laboratory conditions. These results indicate that the system meets the fundamental requirements of real-time performance, accuracy, and stability for health and safety monitoring of elderly individuals living alone[12,17].

7. Conclusion and outlook

This paper presents the design and implementation of an STM32-based health and safety monitoring system for elderly individuals living alone. The system integrates multi-source information, including body temperature, heart rate and blood oxygen saturation, motion status, and GPS positioning, and achieves Wi-Fi connectivity to a cloud platform through an ESP32 module, enabling caregivers to remotely access health data and alarm information. The system performs local threshold-based evaluation and alarm triggering, while synchronously uploading abnormal data to the cloud. Experimental results demonstrate that the proposed system exhibits good performance in vital sign monitoring, fall detection, positioning accuracy, and wireless communication stability, indicating strong practicality and application potential. Future work will focus on incorporating intelligent algorithms, expanding sensor modalities, and enhancing data security and privacy protection to further improve system intelligence and reliability[2,19].

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