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A Low-Cost Customizable Multi-Parameter Eye-Health Monitoring System for Adolescent Myopia Prevention

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ABSTRACT In recent years, the prevalence of myopia among adolescents has increased continuously. Improper viewing distance, inappropriate ambient illumination, and prolonged continuous near-work are the major inducing factors for visual impairment. Aiming at the drawbacks of existing eye-protection devices, such as single-function design, fixed-parameter configuration and poor adaptability, this paper designs a multi-parameter intelligent eye-protection monitoring system with user-customizable thresholds based on a 51-series microcontroller. The system integrates an ultrasonic ranging module, an analog-to-digital converter illumination acquisition circuit, a key-operated threshold adjustment interface, a liquid-crystal display module, and an audio-visual alarm unit. Different from conventional fixed-threshold schemes, the proposed system adopts user-customizable thresholds. The audio-visual alarm will be automatically triggered once any of the indicators including illumination intensity, viewing distance or eye-using duration exceeds the preset safety thresholds. Proteus simulation and physical prototype test results demonstrate that the ranging error of the system is within ±1 cm, the illumination acquisition error is less than 5 %, and the abnormal-event response time is lower than 1 s. Featuring low cost, simple human-computer interaction and favorable expandability, the system can effectively assist users in standardizing their eye-using behaviors and possesses promising practical application prospects.

KEYWORDS 51-series microcontroller, embedded systems, eye-protection monitoring system, human-computer interaction, illumination measurement, ultrasonic ranging

I. INTRODUCTION

In recent years, earlier-onset and rising-prevalence adolescent myopia has become a major public-health issue worldwide. According to projections from the World Health Organization, the global myopic population will reach 4.758 billion by 2050, accounting for 49.8% of the global population [1]. Numerous medical studies have demonstrated that unhealthy visual habits, such as prolonged near-work, improper sitting postures, and reading under excessively dim or bright ambient light, constitute major risk factors for the onset and progression of myopia [2]. Therefore, developing intelligent devices for real-time monitoring of visual-use environments and bad-habit reminders is of great clinical value and social significance for myopia prevention and eyesight protection in daily study and life.

At present, domestic and international research on eye-health monitoring mainly falls into two technical categories. The first category employs machine-vision-based algorithms for posture and viewing-distance recognition. Although such algorithms achieve relatively high recognition accuracy, they suffer from obvious drawbacks: high hardware cost, substantial computing-power requirements, unsatisfactory privacy protection, and difficulties for portable deployment [3]. The second category refers to embedded-sensor-based monitoring solutions. Owing to their advantages of low cost, low power consumption, wearability and favorable real-time performance, embedded-sensor solutions have become a mainstream research direction for eye-protection equipment in recent years [4]. Nevertheless, most existing embedded monitoring devices still exhibit prominent technical limitations. Most commercially available smart wearable eye-protection systems monitor visual-use behaviors relying on factory-preset fixed thresholds for viewing distance and ambient illumination intensity [5]. Such fixed-parameter schemes show poor universality and adaptability. Preset fixed thresholds cannot accommodate users with different heights, visual habits and visual conditions [6]. Consequently, they fail to meet the requirements for personalized and precise eye-protection monitoring and frequently produce false-positive or false-negative alarms [7]. Bhattacharya et al. in the field of wearable health monitoring showed that fixed thresholds ignore inter-patient severity differences and make suboptimal trade-offs between sensitivity and false alarms: the false positive rate (FPR) at a fixed 0.5 cut-off is as high as 32.6%, and even with the Youden's J optimal cut-off, the FPR remains 38.6% [8]. Furthermore, several reported wearable monitoring devices merely record viewing distance and visual-use duration without integrating ambient-illumination detection; hence, joint monitoring of reading-writing distance, ambient-light intensity and accumulated continuous visual-use time cannot be realized [9].

To address the above-mentioned limitations, this paper implements a low-cost prototype of an intelligent eye-protection system based on the STC89C52RC 51-series microcontroller. An HC-SR04 ultrasonic module is adopted to acquire reading-writing distance information [10]. A light-dependent resistor (LDR) combined with the ADC0832

serial analog-to-digital conversion chip (ADC) is utilized to sample ambient-light intensity [11]. Independent push-buttons are configured so that users can customize three alarm-threshold types for viewing distance, illumination intensity and cumulative visual-use duration. Once any monitored parameter exceeds the user-defined threshold, the device automatically activates audio-visual reminders to intervene against improper visual-use behaviors in real time. Compared with conventional monitoring equipment, the proposed system realizes multi-dimensional fusion monitoring of eye-use risks and personalized adaptive judgment. It effectively resolves the well-known limitations of fixed-threshold strategies including poor universality and insufficient monitoring dimensions. Balancing practicality and adaptability under a low-cost embedded architecture, this work can provide references for designing and optimizing personalized myopia-prevention devices for adolescents.

II. CONCLUSION

This work develops a low-cost multi-parameter eye-health monitoring system with user-customizable thresholds for adolescent myopia prevention. Unlike conventional eye-protection devices that adopt factory-preset fixed thresholds, the presented system supports personalized calibration of viewing distance, ambient illumination, and continuous near-work duration through simple keystroke operations. Audio-visual reminders will be triggered in real time once any monitored parameter exceeds user-defined safety limits to mitigate improper eye-using behaviors.

Proteus simulation and physical prototype experiments are performed to verify system functions and performance. Experimental results demonstrate that the ranging error is within ±1 cm, the illumination sampling error is less than 5 %, and the response latency for abnormal eye-use events is below 1 s. Owing to the customizable-threshold mechanism, false alarms induced by universal fixed-parameter configurations can be effectively suppressed.

Featuring low cost and favorable expandability, the proposed system provides a practical reference for the design of personalized myopia-prevention hardware. Future research will optimize alarm feedback mechanisms and conduct long-term tests under real household conditions to further improve practical usability.

III. METHODS

A. SYSTEM OVERALL SCHEME

Taking the STC89C52RC single-chip microcontroller as the core controller, the system realizes the intelligent eyes-protection function with external sensors, display module and alarm module. The system mainly consists of the single-chip microcontroller minimum system, distance-detection module, illumination-detection module, display module, alarm-reminder module, key-button setting module and power-supply module. Each module is connected through the I/O ports of the microcontroller. The microcontroller is responsible for data acquisition, state judgment, display control and alarm output. The overall block diagram of the system is shown in Figure 1.

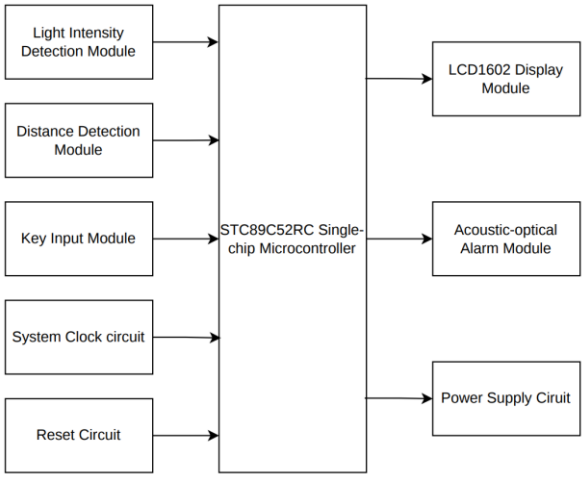


FIGURE 1. **Overall block diagram of the system**

The ultrasonic distance-measurement module detects the distance between the user and books or the desktop, and transmits measured signals to the microcontroller. The illumination-detection module detects the light intensity of the learning environment and sends illumination information to the microcontroller. The microcontroller makes comprehensive judgments on distance, illumination and eye-use time according to preset thresholds. The LCD1602 liquid-crystal display module shows the current system state. The acoustic-optical alarm-reminder module gives warnings under abnormal conditions. The key-button module is adopted to calibrate the distance threshold, adjust the time threshold or switch display states. The whole system forms a closed-loop reminding process: external information is collected by sensors; the microcontroller judges whether a reminder is required; feedback is finally provided to the user via the display and alarm modules. The overall flowchart of the system is shown in Figure 2.

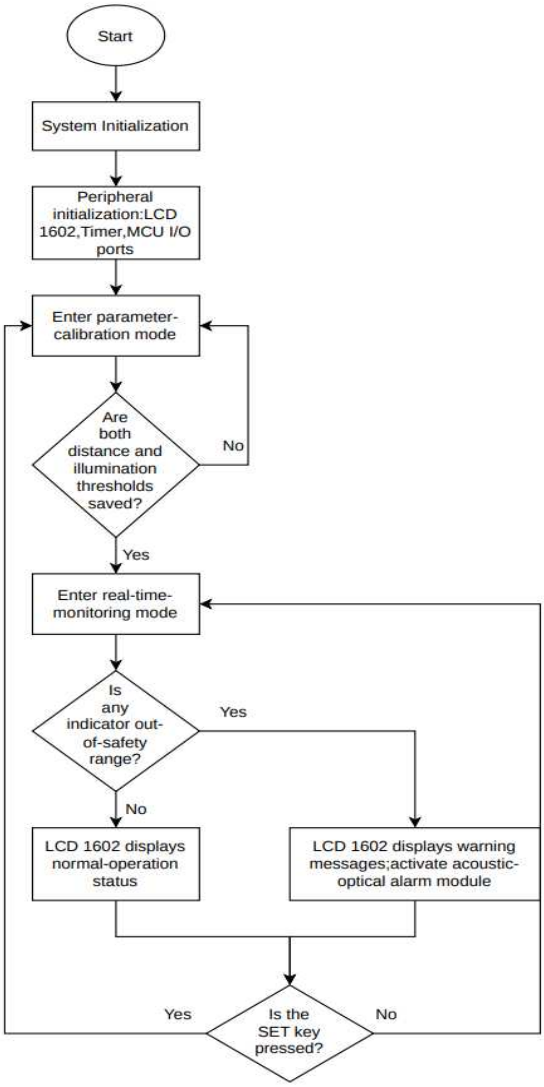


FIGURE 2. **Overall workflow diagram of the system**

1) SINGLE-CHIP MICROCONTROLLER CONTROL MODULE

The single-chip microcontroller control module serves as the core of the entire system. In this design, the STC89C52RC microcontroller is adopted as the main-control chip. Belonging to the 51-series microcontrollers, it exhibits favorable compatibility and stability, which can satisfy the requirements of data acquisition, logical judgment and peripheral-device control for the proposed system. The microcontroller mainly receives signals transmitted from the

distance-detection module and illumination-detection module, processes the acquired data, and drives the liquid-crystal display module and alarm module according to judgment results. Within the presented system, the main tasks of the microcontroller are as follows: controlling the ultrasonic module to realize distance measurement; reading output signals from the illumination-detection module; accumulating eye-use time by means of a timer; controlling the LCD1602 module to display the current system status; triggering alarms via the buzzer or voice module; reading key-button inputs and modifying relevant parameters. Reasonable allocation of I/O-port resources enables coordinated operation among all functional modules.

2) DISTANCE-DETECTION MODULE

The distance-detection module is mainly used to judge whether the user is too close to books or the desktop during learning. In this design, the HC-SR04 ultrasonic ranging module is adopted for distance detection. This module generally consists of a Trig trigger pin and an Echo echo pin. After the microcontroller sends a trigger signal to the Trig pin, the ultrasonic module transmits ultrasonic waves. Upon receiving the reflected signal, it outputs a high-level pulse through the Echo pin. The microcontroller calculates the distance between the measured object and the module by measuring the duration of the high-level pulse at the Echo pin.

3) ILLUMINATION-DETECTION MODULE

The illumination-detection module is applied to evaluate the light condition of the learning environment. In this design, the illumination-detection module is composed of a photoresistor and ADC0832 to realize light-intensity detection. The resistance value of the photoresistor varies with the ambient light-intensity. The resistance decreases under strong-light conditions and increases when the light is weak. Combined with a voltage-dividing resistor or comparator circuit, variations in illumination can be converted into voltage signals or digital signals recognizable by the microcontroller.

4) TIMING-REMINDER MODULE

The timing-reminder module is mainly used to count the continuous eye-use duration of the user during reading and learning. Eyes are prone to fatigue under long-time close-range visual work. Therefore, the system will trigger a rest reminder once the eye-use duration reaches the preset value. In this design, the built-in timer of the microcontroller is utilized to realize time-accumulation function. After the system starts, the timer generates interrupts at fixed time intervals. The program performs counting in the interrupt service function to accumulate the eye-use time.

5) DISPLAY MODULE

The display module realizes human-computer interaction, allowing users to intuitively observe the current system status. In this design, the LCD1602 liquid-crystal display screen is adopted as the display module. The LCD1602 can display two lines of characters with 16 characters per line. The system can present the measured distance, illumination status, eye-use time and alarm prompt information on the liquid-crystal screen.

6) ALARM-REMINDER MODULE

The alarm-reminder module provides timely reminders when abnormal conditions are detected. A buzzer is employed for alarm output in this design. Featuring simple circuit structure,

low cost and convenient control, the buzzer is suitable to serve as a basic alarm unit. When the system detects excessively short viewing distance, insufficient illumination or excessive eye-use duration, the microcontroller outputs control signals to drive the buzzer for sound alarm.

7) KEY-BUTTON SETTING MODULE

The key-button setting module enables parameter modification and function switching. Several independent push-buttons are configured in this design, including the mode key, lock key and reset key. The mode key is used to switch configuration items. The lock key and reset key are utilized to modify the initial thresholds. With the key-button module, users can adjust alarm thresholds according to individual requirements. The introduction of the key-button module improves the human-computer interaction performance of the system, so that the system is no longer operated merely relying on fixed parameters.

B. HARDWARE-CIRCUIT DESIGN AND PROTEUS SIMULATION

1) MINIMUM-SYSTEM CIRCUIT OF SINGLE-CHIP MICROCONTROLLER

The minimum-system circuit of the STC89C51 single-chip microcontroller consists of a power-on reset circuit and a clock circuit. The clock circuit relies on a crystal oscillator to generate periodic oscillation signals and serves as the "heart" of the microcontroller. A higher clock frequency results in a shorter instruction-execution cycle and faster execution speed of the microcontroller. Generally, 51-series microcontrollers can adopt a 12 MHz crystal oscillator or a 32.768 kHz crystal oscillator, together with two 22 pF filter capacitors. The reset circuit is composed of a 10 μF capacitor, a 10 kΩ resistor and a reset button. It implements power-on reset and manual reset of the system.

2) DISPLAY MODULE

The display module presents the operating status and detection results of the intelligent eyes-protection device. In this design, the LCD1602 liquid-crystal display screen is adopted as the human-computer interaction display component. An 8-bit parallel data transmission mode is employed to facilitate data transmission and simplify programming. Data pins D0-D7 of the LCD1602 are connected to P0.0-P0.7 ports of the STC89C52RC microcontroller for 8-bit parallel transmission, which realizes intuitive data display and concise program control. RS serves as the register-selection pin and is connected to P2.0 of the microcontroller to distinguish command-write operations from data-write operations. E is the enable pin connected to P2.1 to control data reception of the LCD. The RW pin is the read-write control pin and is directly grounded, so that the liquid-crystal screen operates in the write-only mode. Since the P0 ports of the 51-series microcontroller require external pull-up resistors when used as general-purpose I/O ports, a 10 kΩ resistor pack is connected externally to P0.0-P0.7 as pull-up resistors to stabilize the logic level on data lines. The VO pin of LCD1602 is connected to a 10 kΩ potentiometer for display-contrast adjustment. The backlight pin A is connected to +5 V through a 220 Ω current-limiting resistor, while pin K is connected to ground.

3) ACOUSTIC-OPTICAL ALARM MODULE

The acoustic-optical alarm module reminds users when the system detects excessively short viewing distance, insufficient

illumination or excessively long continuous eye-use duration. Low-level triggering is adopted in this design, and an S8550 PNP transistor is selected as the driving device. The P1.7 port of the microcontroller is connected to the base of the S8550 through a 1 kΩ current-limiting resistor. The emitter of the transistor is connected to the +5 V power supply. Its collector is connected to the positive terminal of the active buzzer and the branch circuit of the LED indicator. The negative terminal of the buzzer is connected to ground. The LED indicator is connected to the collector of the transistor via a 1 kΩ current-limiting resistor and then to ground. Moreover, a 10 kΩ pull-up resistor is connected between the transistor base and the +5 V power supply, so that the alarm module remains off when the microcontroller does not output control signals. When the P1.7 pin outputs a low-level signal, the S8550 transistor turns on. The buzzer is powered on to produce sound, and the LED indicator lights up to realize acoustic-optical alarm. When P1.7 outputs a high-level signal, the transistor cuts off, and both the buzzer and the LED stop working. This design conforms to the control logic of conventional low-level-triggered alarm modules. It features simple circuit structure, obvious reminder effect and high reliability.

4) KEY-BUTTON SETTING MODULE

The key-button setting module realizes system-parameter configuration and working-mode switching. Three independent push-buttons are arranged in this design: the setting key, the lock key and the reset key. The setting key is connected to the microcontroller pin P1.0, the lock key to P1.1, and the reset key to P1.2. The keys adopt an active-low mode. One terminal of each push-button is connected to the microcontroller I/O pin, and the other terminal is connected to system ground. When a key is not pressed, the microcontroller pin maintains a high-level state. When a key is pressed, the corresponding pin is pulled low. After detecting the low-level signal, the microcontroller executes the corresponding function. To avoid false triggering caused by mechanical-key jitter, a software-based delay debouncing algorithm is adopted in the program. With this key-button module, users can adjust parameters such as the distance threshold and eye-use-time threshold, which improves the human-computer interaction capability of the system.

5) ILLUMINATION-DETECTION MODULE

The illumination-detection module collects light intensity information of the learning environment. Since the STC89C52RC microcontroller has no on-chip A/D conversion function, it cannot directly read the analog voltage generated by the photoresistor. Therefore, the ADC0832 analog-to-digital conversion chip is employed in this design to acquire illumination signals. ADC0832 is an 8-bit serial A/D converter with two analog input channels. CH0 denotes Channel 0, which converts analog voltage within the range of 0-5 V into digital values and communicates with the microcontroller via serial interface. In this design, the photoresistor LDR1 and the 10 kΩ resistor R7 form a voltage-divider circuit. The voltage at the voltage-dividing node varies with ambient light intensity. This node is connected to the CH0 channel of ADC0832. The CS, CLK, DI

and DO pins of ADC0832 correspond to chip-select, clock, data input and data output respectively, and are connected to P1.3, P1.4, P1.5 and P1.6 pins of the STC89C52RC microcontroller. By controlling the CS and CLK signals, the microcontroller selects the conversion channel through DI and reads the converted 8-bit digital value from DO. The program compares the sampled illumination value with the preset threshold. When the sampled value is lower than the threshold, the system judges that the illumination is insufficient and triggers the acoustic-optical alarm together with prompt messages on LCD1602. This module can not only judge insufficient-illumination conditions, but also convert light intensity into specific digital values for display. Hence, it is well-suited for the intelligent eyes-protection device requiring data display and threshold adjustment.

6) ULTRASONIC RANGING MODULE

The ultrasonic ranging module detects the distance between the user and the learning desktop or books. The HC-SR04 ultrasonic ranging module is adopted as the distance-sensing component in this design. This module has four pins: VCC, TRIG, ECHO and GND. VCC is the positive power-supply pin connected to +5 V; GND is the ground pin connected to system ground. The TRIG pin is the trigger input terminal for receiving trigger pulses sent by the microcontroller, and it is connected to pin P3.7 of the STC89C52RC microcontroller. The ECHO pin is the echo-output terminal, which outputs a high-level pulse proportional to the measured distance, and it is connected to microcontroller pin P3.2. To improve power-supply stability of the module, a 0.1 μF decoupling capacitor is connected in parallel across the power-supply terminals of the module. During system operation, the microcontroller sends trigger pulses to the ultrasonic module via the TRIG pin. Then the module transmits ultrasonic waves. After the reflected echo signal is received, a high-level pulse is generated at the ECHO pin. The microcontroller measures the duration of the high-level pulse on the ECHO pin using its timer, and calculates the distance according to the propagation time of sound waves in air. If the measured distance is smaller than the preset threshold, the system determines that the user is too close. Prompt information will be displayed on the liquid-crystal screen, and the acoustic-optical alarm module will be activated simultaneously to remind the user. Featuring simple wiring and intuitive distance-measurement performance, this module is well-suited for distance-detection functions of the intelligent eyes-protection device.

C. SOFTWARE PROGRAM DESIGN

The software of the proposed eye-protection system is developed under Keil uVision5, an integrated development environment for 8051-core microcontrollers. It provides built-in source-code editing, C51 compiling, linking and debugging functions. After compilation, the HEX file is generated and downloaded to the STC89C52RC microcontroller via the STC-ISP programming tool for hardware verification. The software follows the workflow: initialization-forced threshold calibration-data acquisition-threshold judgment-display refresh-audio-visual alarm. After power-on, the microcontroller configures I/O ports, initializes LCD1602A, configures timers and assigns

initial values to global variables. The system then directly enters the user-defined calibration interface. The SET key is used to switch among calibration items including distance, illumination and eye-using time. After users press the LOCK key for confirmation, the current environmental parameters are stored as operating thresholds, and the main loop starts. In the main loop, key detection, illumination sampling, ultrasonic distance measurement, comparison with user-calibrated thresholds, alarm control and LCD refresh are executed periodically. Once insufficient illumination, too-short reading distance or overrun of calibrated eye-using time is detected, the alarm flag is set, and the buzzer is triggered for audio-visual reminder.

The main program adopts a cyclic polling architecture. Firstly, the system-initialization function is invoked to configure the initial logic level of each I/O port, set the timer mode, and initialize the LCD1602. Subsequently, the system enters the mandatory-threshold-calibration stage. After the user completes parameter configuration and confirms via the LOCK key, the user-defined thresholds overwrite the global-threshold variables, and then the infinite main-loop is activated. Within each loop iteration, key-scan, illumination sampling, distance measurement, threshold comparison, alarm-logic processing and display refresh are executed sequentially.

In terms of program architecture, the main program is only responsible for process scheduling instead of handling complex peripheral timing directly. LCD-related operations are implemented by the display subroutine. The serial-timing logic of ADC0832 is realized by the acquisition subroutine. Trigger signal generation and echo-time measurement for the HC-SR04 ultrasonic module are completed by the distance-measurement subroutine. Key-debouncing and key-function recognition are handled by the key-processing subroutine. Finally, the alarm subroutine controls the output state of pin P1.7 according to the alarm flag bit to drive the audio-visual alarm. This modular subroutine division greatly reduces the complexity of the main program. Each functional module possesses good readability and facilitates debugging and maintenance.

1) DESIGN OF ILLUMINATION ACQUISITION SUBROUTINE

In this design, the voltage-dividing node of the photoresistor is connected to CH0 of ADC0832, while CH1 is not utilized in the software functions described in this chapter. The core task of the ADC acquisition subroutine is as follows: pull the CS pin low, transmit three control bits, i.e., Start=1, SGL/DIFF=1, and ODD/SIGN (channel-number bit). After inserting one dummy clock pulse, 8-bit data is read continuously. If the current reading from CH0 is lower than the user-calibrated illumination threshold, the illumination alarm flag is asserted.

2) DESIGN OF ULTRASONIC DISTANCE-MEASUREMENT SUBROUTINE

In this design, the distance measurement is realized by combining polling and timer-based pulse-width measurement. First, a trigger pulse longer than 10 μs is output, and then the rising edge of the ECHO pin is awaited. When ECHO changes from low to high level, the timer counter is cleared and the timer is started. The timer is stopped once ECHO falls back to

low level. Finally, the measured counter value is converted into distance by the formula \(distance_cm \approx timer_count / 53\).

3) DESIGN OF TIMING SUBROUTINE

In this design, the continuous study or reading time of the user can be accumulated. An automatic rest reminder will be triggered once the time exceeds the user-calibrated time threshold. Illumination detection judges whether the learning environment is too dim, distance detection judges whether the reading posture is too close, and timing detection judges whether the continuous eye-using duration is excessive. These three functions constitute the core protection mechanism of the intelligent eyesight protector. All three detection results participate jointly in alarm judgment. Consequently, the system can remind users from three dimensions including environment, posture and time, which improves the practicability and integrity of the system.

4) DESIGN OF AUDIO-VISUAL ALARM SUBROUTINE

The alarm module in this design adopts a low-level-triggered structure. Hence, the core of the audio-visual alarm subroutine lies in logical judgment rather than complicated timing control. When the illumination value is lower than the threshold, the accumulated time reaches the calibrated time threshold, or the measured distance is smaller than the distance threshold, the corresponding alarm flag bit is set to 1. Provided that any alarm flag is valid, the program outputs a low-level signal at pin P1.7 to drive the buzzer and LED to work simultaneously.

D. SYSTEM PERFORMANCE TEST

1) PROTEUS SIMULATION AND PHYSICAL PROTOTYPE TEST

This chapter conducts simulation and physical-prototype verification for the functions of the eyesight-protection device. In the Proteus simulation, a variable potentiometer is adopted to replace the actual voltage-dividing circuit of the photoresistor, so as to conveniently simulate different ambient-light conditions. The complete simulation circuit is shown in Figure 3. The complete physical diagram is shown in Figure 4.

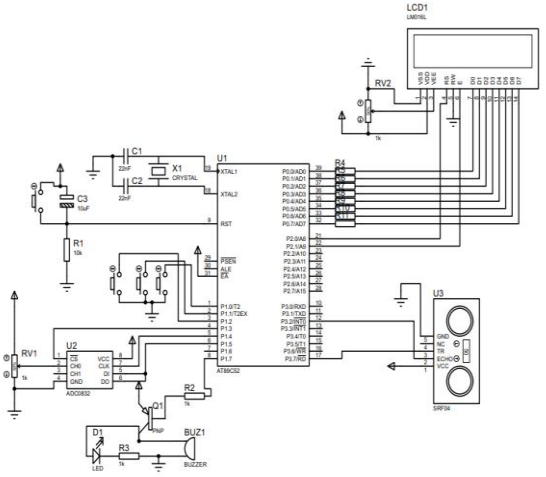


FIGURE 3. Simulation circuit diagram

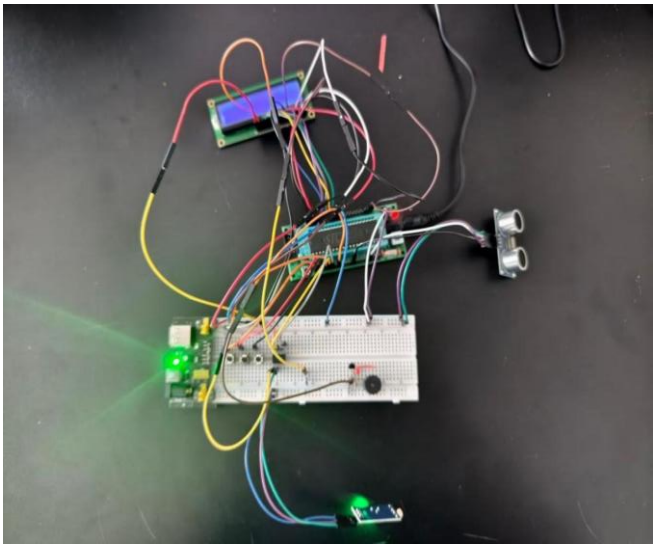


FIGURE 4. Prototype photograph

The complete circuit is constructed and simulated in the virtual environment of Proteus. The single-chip microcontroller clock is set to 11.0592 MHz, and the trigger pulse width is 20 μs. Channel CH0 of ADC0832 adopts a potentiometer to simulate the input of illumination-related voltage. Tests are performed by applying 0 V and 5 V to CH0 successively in simulation. The results show that the ADC outputs are approximately 0 and 255 respectively, which agrees with the theoretical conversion relationship (0-5 V corresponding to 0-255). In the illumination-threshold setting experiment, the system switches from normal state to "insufficient illumination" alarm state when the ADC sampled value drops from 80 to 77. In the distance-threshold test, the system alarm flag toggles when the actual distance decreases from 31 cm to 29 cm, which meets the expectation. Repeated measurements demonstrate that the error of ultrasonic ranging is within 1 cm, as listed in Table 1, and the illumination detection error is less than 5 %, as shown in Table 2. The system operates stably and reliably. The simulation results are in good agreement with both the design specifications and physical prototype, which verifies the correctness of module functions and alarm logic.

TABLE 1

Ultrasonic ranging measurement data

Test No.	Input Condition	Test Result
01	Actual distance = 10 cm	D = 10 cm
02	Actual distance = 15cm	D = 15cm
03	Actual distance = 20cm	D = 20cm
04	Actual distance = 25cm	D = 25cm
05	Actual distance = 30cm	D = 30cm
06	Actual distance = 35cm	D = 35cm
07	Actual distance = 40cm	D = 40cm
08	Actual distance = 45cm	D = 45cm
09	Actual distance = 50cm	D = 50cm
10	Actual distance = 60cm	D = 60cm

TABLE 2

Illumination detection data

Input Condition	Expect Result	Test Result
CH0 = 0.5V	L = 25.5	L = 26
CH0 = 1.0V	L = 51	L = 51
CH0 = 1.5V	L = 76.5	L = 77
CH0 = 2.0V	L = 102	L = 102
CH0 = 2.5V	L = 127.5	L = 128
CH0 = 3.0V	L = 153	L = 153
CH0 = 3.5V	L = 178.5	L = 179
CH0 = 4.0V	L = 204	L = 204
CH0 = 4.5V	L = 229.5	L = 230
CH0 = 5.0V	L = 255	L = 255

2) PILOT CLINICAL TRIAL

To further verify the practical performance, alarm-recognition accuracy and actual effect of the customizable-threshold function of the proposed eye-health monitoring system under real-world usage scenarios, a small-scale feasibility pilot clinical trial was carried out with adolescent participants. Different from the electrical-parameter calibration tests in laboratory environments, this trial evaluated the comprehensive performance of the system in simulated home

reading and near-work scenarios, including the adaptation effect of personalized threshold calibration, true-positive rate, false-positive rate, and subjective human-machine interaction experience of participants.

A total of 22 adolescent participants were recruited, aged from 10 to 16 years old with an average age of 13.1±1.8 years, including 12 males and 10 females.

Inclusion criteria:

1) Age ranged from 10 to 16 years old.
2) Daily total near-work duration was no less than 2 h, including homework, paper reading, online courses via electronic devices, etc.
3) Capable of completing device threshold calibration independently and skillfully operating the keys of the prototype.
4) Voluntarily participated in this trial, and written informed consent was obtained from participants and their legal guardians.

Exclusion criteria:

1) Suffered from ocular organic diseases other than myopia, such as strabismus, amblyopia and severe refractive interstitial abnormality.
2) Unable to maintain basic reading-writing sitting posture and complete the whole trial procedure.
3) Participants or their guardians refused to sign the informed consent document.

All participants used the hardware prototype to complete a 40-minute simulated home near-work task in a simulated home-study environment. The complete trial procedure is described as follows:

1) Before formal testing, each participant completed personalized threshold calibration following the system workflow. Participants adjusted to their comfortable standard reading-writing posture and pressed the lock key to save three safety thresholds: viewing distance, ambient illumination and continuous near-work duration. When ambient light changed obviously, participants could press the reset key to recalibrate thresholds.
2) Participants performed reading and writing tasks naturally. Researchers did not intervene in sitting posture or head position. The device automatically recorded viewing distance, ambient illumination, accumulated near-work time and all alarm events throughout the test.
3) Two trained researchers performed manual observation and recording simultaneously. The researchers manually judged the real eye-using status of participants (too short viewing distance, abnormal light intensity, overtime continuous near-work), which was regarded as ground-truth for comparison and statistics with alarms output by the device.
4) After the 40-minute trial, participants finished a short subjective-experience questionnaire. The questionnaire covered dimensions including operation difficulty, rationality of alarm reminders, adaptation experience of customizable thresholds, and disturbance degree of audio-visual reminders. A

1-5 Likert scale (1 = worst, 5 = best) was adopted for scoring.

Main evaluation indicators of this pilot trial are listed below:

1) True-Positive Rate (TPR): the proportion of correctly triggered alarms when bad eye-using behaviors actually occur.
2) False-Positive Rate (FPR): the proportion of falsely triggered alarms under normal eye-using status.
3) Subjective evaluation indicators: ease of operation, rationality of customizable thresholds and disturbance of audio-visual alarms, all scored on a 1-5 scale.

Table 3 summarizes the statistical results of this pilot clinical trial.

TABLE 3

Results of adolescent pilot clinical trial (N=22)

Evaluation indicator	Value
True-positive alarm rate (TPR)	89.2 %
False-positive alarm rate (FPR)	8.6 %
Average score of operation easiness (1-5 scale)	4.14±0.51
Average score of customizable-threshold rationality (1-5 scale)	4.27±0.48
Average disturbance score of audio-visual alarm (1-5 scale)	2.26±0.42

Benefiting from the user-customizable threshold design, the prototype can adapt to adolescent participants with different heights and reading habits. For bad eye-using events in real scenarios, the average response latency of the system is less than 1 s, which is consistent with the time-performance obtained from laboratory prototype tests.

Subjective questionnaire feedback shows that most adolescent participants can quickly master the key-driven threshold-calibration operation. Several participants reported that the alarm volume was relatively large and expected volume adjustment or vibration reminder mode in subsequent versions. No participant reported physical discomfort or adverse events caused by the device during the whole trial.

The trial results demonstrate that customizable thresholds can effectively reduce false alarms induced by unified factory preset parameters, which is the core advantage of the proposed system compared with traditional fixed-threshold eye-protection devices.

Limitations of this pilot trial should be noted. The sample size is limited, and the trial was conducted in a controlled simulated home environment rather than long-term follow-up in real household scenarios. In future research, the number of participants will be expanded to carry out long-term home-based field trials. Meanwhile, alarm modes will be optimized according to user feedback, vibration reminders and multi-level volume adjustment will be added to further improve practical user experience.

Written informed consent was obtained from all adolescent participants and their legal guardians for the pilot trial.

No participant reported physical discomfort or adverse events caused by the device during the whole trial.

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

IV. DECLARATIONS

A. Ethics approval and consent to participate

This study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of Shandong Second Medical University. Written informed consent to participate was obtained from the legal guardians of all participants. For participants under 16 years of age, written informed consent was obtained from their parents or legal guardians, and assent was obtained from the participants themselves. All participants voluntarily agreed to take part in this study.

B. Consent for publication

Not applicable.

C. Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

D. Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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F. Authors' contributions

Y.B. conceived and designed the overall system, and independently drafted the original manuscript. J.W. and Y.K. were responsible for the construction of the physical hardware prototype, circuit assembly, and module debugging. They also conducted the pilot clinical trial (including participant recruitment, data collection, and statistical analysis), performed the Proteus simulations, and prepared all the figures and tables (including Figures 1-4 and Tables 1-3). Z.C. provided overall supervision and critically revised the manuscript. All authors read and approved the final manuscript.

G. Acknowledgements

Not applicable.

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