

Development of a Multi-Modal Biofeedback System for Stress Reduction: Integration of Galvanic Skin Response and Heart Rate Monitoring

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We present the design, implementation, and evaluation of a comprehensive biofeedback system integrating galvanic skin response (GSR) and photoplethysmography (PPG) heart rate monitoring with multi-modal feedback mechanisms. The system employs an Arduino UNO R4 WiFi microcontroller to process physiological signals and provide real-time visual (LED) and auditory (tonal) feedback to guide users toward relaxation states. Our implementation demonstrates the feasibility of low-cost, accessible biofeedback technology for stress management applications. Preliminary testing revealed the importance of sensor placement optimization and the effectiveness of graduated feedback zones in promoting physiological self-regulation.

INTRODUCTION

Biofeedback represents a well-established therapeutic technique wherein individuals learn to modify physiological processes through real-time monitoring and feedback [1]. The fundamental principle relies on the closed-loop interaction between conscious awareness and autonomic nervous system responses. By providing immediate information about physiological states—such as heart rate, skin conductance, or muscle tension—biofeedback enables users to develop voluntary control over typically involuntary processes.

The autonomic nervous system (ANS) governs involuntary physiological functions, divided into sympathetic (“fight or flight”) and parasympathetic (“rest and digest”) branches. Stress activates the sympathetic nervous system, manifesting in increased heart rate and galvanic skin response. Biofeedback training aims to enhance parasympathetic activation, promoting relaxation and stress reduction [2].

Modern biofeedback applications have expanded beyond clinical settings into consumer wellness devices, enabled by advances in low-cost sensing technology and embedded systems. This project explores the integration of multiple physiological sensors with intuitive feedback mechanisms to create an accessible stress management tool.

BACKGROUND AND RELATED WORK

Galvanic Skin Response

Galvanic skin response (GSR), also termed electrodermal activity (EDA), measures variations in skin electrical conductance resulting from eccrine sweat gland activity [3]. The eccrine glands, controlled by the sympathetic nervous system, respond to emotional arousal and cognitive load. Increased sympathetic activation causes subliminal perspiration, elevating skin conductance even before

moisture is perceptible.

GSR has been extensively utilized in psychophysiology research, lie detection, and affective computing applications. Its sensitivity to emotional states makes it particularly valuable for stress monitoring. The Seeed Studio GSR sensor employed in this project utilizes a voltage divider circuit to convert resistance changes into analog voltage signals suitable for microcontroller processing.

Photoplethysmography

Photoplethysmography (PPG) is an optical technique for measuring blood volume changes in peripheral tissue [4]. A light-emitting diode (LED) illuminates tissue, and a photodetector measures reflected or transmitted light intensity. Cardiac contractions cause pulsatile blood flow, creating periodic variations in light absorption. Digital signal processing of the PPG waveform yields heart rate and beat-to-beat interval measurements.

Heart rate variability (HRV)—the variation in time intervals between consecutive heartbeats—serves as an important marker of autonomic nervous system balance. Reduced HRV typically indicates sympathetic dominance and stress, while increased HRV suggests parasympathetic activation and relaxation [5].

Biofeedback Training Protocols

Effective biofeedback systems require carefully designed feedback protocols. Research indicates that multi-modal feedback (combining visual, auditory, and haptic channels) enhances learning and engagement compared to single-modality approaches [6]. Progressive feedback—where reward intensity corresponds to achievement level—has demonstrated superior outcomes in promoting behavioral change.

Heart rate coherence training, a specific biofeedback protocol, guides users toward rhythmic breathing patterns that synchronize heart rate variability with respi-

ration. This technique has shown efficacy in reducing anxiety, improving emotional regulation, and enhancing cognitive performance [7].

SYSTEM DESIGN AND IMPLEMENTATION

Hardware Architecture

Our biofeedback system integrates the following components:

- **Microcontroller:** Arduino R4 WiFi (Renesas RA4M1, ARM Cortex-M4, 48 MHz)
- **Physiological Sensors:**
 - Pulse Sensor (PPG-based heart rate monitor)
 - Sreed Studio GSR Module (Grove GSR Sensor)
- **Feedback Mechanisms:**
 - Four-color LED array (red, yellow, green, blue)
 - 8Ω 0.5W speaker (Adafruit 1890)
- **Supporting Components:**
 - Current-limiting resistors (220Ω for each LED)
 - Breadboard and jumper wires for prototyping

Circuit Configuration

The complete circuit schematic is shown in Fig. 1. The pulse sensor connects to analog input A0, providing a continuous PPG waveform. The GSR sensor interfaces with analog input A1, outputting voltage proportional to skin conductance. Both sensors receive 5V power from the Arduino’s regulated supply.

The LED outputs utilize digital pins 2–5, with series resistors chosen to keep each LED current within the UNO R4 WiFi’s recommended per-pin I/O current rating (8 mA for the RA4M1 microcontroller). The speaker connects to digital pin 6, driven by the Arduino’s hardware PWM capability for tone generation.

Signal Processing

Heart Rate Detection

The pulse sensor library implements real-time beat detection using adaptive thresholding. The algorithm identifies systolic peaks in the PPG waveform and calcu-

lates inter-beat intervals (IBI). A 550 ADC count threshold was empirically determined for reliable detection under laboratory conditions. Exponential smoothing filters ($\alpha = 0.10$ for BPM, $\alpha = 0.20$ for raw signal) reduce measurement noise while maintaining responsiveness.

GSR Baseline Calibration

GSR exhibits substantial inter-individual variability, necessitating personalized baseline calibration. Upon system initialization, the user places fingers on the sensor electrodes for a 5-second calibration period. During this interval, the system applies exponential smoothing ($\alpha = 0.05$) to establish an individual baseline. Subsequent measurements are expressed as deviations from this baseline, enabling standardized stress level classification.

Feedback Design

Zone-Based Classification

We implemented a seven-zone classification system mapping heart rate to physiological states:

TABLE I. Heart rate zones and feedback parameters

Zone	BPM Range	LED Color	Tone (Hz)	Rate (ms)
0	0–59	Blue	220	1000
1	60–69	Green+Blue	262	700
2	70–79	Green	294	500
3	80–89	Yellow+Green	330	400
4	90–99	Yellow	370	300
5	100–119	Red+Yellow	440	200
6	120–250	Red	523	100

The color progression (red → yellow → green → blue) provides intuitive visual feedback, with blue representing the target relaxation state. LED pulse rates decrease with lower heart rates, reinforcing the association between slower physiological rhythms and relaxation.

Auditory Feedback

Tonal frequencies were selected from the musical scale to ensure pleasant, non-jarring audio feedback. Lower zones employ lower pitches (A2 = 220 Hz) associated with calmness, while higher zones use progressively higher frequencies up to C5 (523 Hz). Zone transitions trigger a two-note harmonic interval (perfect fifth) to signal state changes without startling the user.

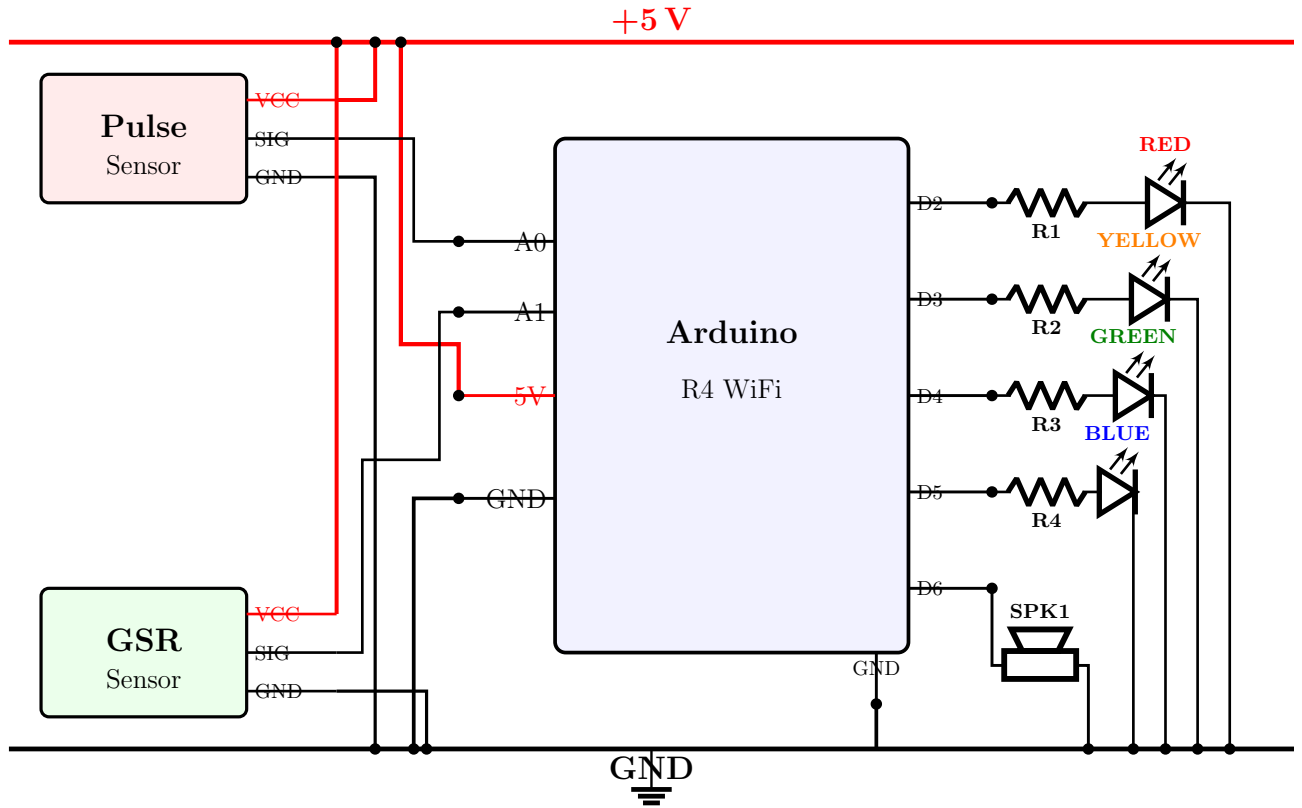


FIG. 1. Circuit schematic of the biofeedback system showing the Arduino R4 WiFi, pulse and GSR sensors, four current-limited LEDs (red, yellow, green, blue), and a speaker connected to digital pin D6 using PWM for tone generation. Power is supplied through common +5V and GND rails. Connection dots indicate junction points between components.

Combined GSR Integration

GSR delta values (deviation from baseline) are classified into five stress levels: Very Relaxed (<10), Relaxed (<30), Moderate (<60), Elevated (<100), and High Stress (≥ 100). The system provides textual encouragement via serial output when users achieve low heart rate combined with low GSR, indicating authentic relaxation rather than mere physical stillness.

EXPERIMENTAL PROTOCOL AND RESULTS

Demonstration Day Protocol

During the laboratory demonstration, multiple participants tested the system under the following protocol:

1. **Setup Phase:** Pulse sensor secured to fingertip using surgical tape; two fingers placed on GSR sensor electrodes
2. **Calibration:** 5-second GSR baseline establishment with participant seated and relaxed

3. **Baseline Measurement:** 30-second recording of initial physiological state
4. **Biofeedback Session:** Participants attempted to lower heart rate using feedback cues (LED color/rate, tone pitch/rate, serial monitor display)
5. **Data Collection:** Serial plotter recorded continuous BPM, GSR, and zone data

Observations

The system successfully provided real-time feedback for most participants. Several participants demonstrated the ability to transition from red/yellow zones (elevated heart rate) to green/blue zones (relaxed state) within 2–3 minutes through controlled breathing techniques.

Technical Challenges

Sensor Contact Issues

The most significant technical challenge involved inconsistent pulse sensor readings. Several instances oc-

curred where the system registered heart rates in the 190–200+ BPM range—physiologically implausible for seated, resting individuals. Investigation revealed these artifacts stemmed from:

- Inadequate sensor-to-skin contact pressure
- Movement artifacts during measurement
- Ambient light interference with the photodetector
- Suboptimal sensor positioning relative to capillary beds

When properly secured with firm but comfortable pressure directly over a capillary-rich area (fingertip pad), the sensor consistently produced accurate readings within the expected 60–100 BPM resting range.

GSR Drift

Minor baseline drift was observed during extended sessions, likely due to:

- Gradual moisture accumulation between electrodes and skin
- Temperature-induced conductance changes
- Electrode polarization effects

The exponential smoothing filter adequately compensated for slow drift, but rapid movements occasionally caused transient artifacts.

DISCUSSION

System Effectiveness

The multi-modal feedback approach proved effective in engaging users and facilitating physiological self-regulation. The graduated zone system provided clear, actionable targets, while the combined visual and auditory feedback created an immersive biofeedback experience. Several participants reported the audio feedback particularly helpful, as it allowed them to maintain focus with closed eyes—a technique commonly employed in relaxation training.

The GSR integration added valuable context to heart rate measurements. In some cases, participants achieved lower heart rates through physical stillness rather than genuine relaxation, evidenced by elevated GSR values. The combined metrics provided a more holistic assessment of relaxation state.

Limitations

Several limitations warrant consideration:

1. **Sensor Reliability:** The consumer-grade pulse sensor required careful placement and securing to maintain signal quality. Clinical-grade sensors with superior signal-to-noise characteristics would enhance reliability.
2. **Individual Variability:** The fixed zone thresholds may not optimally accommodate all users. Resting heart rates vary substantially across individuals based on fitness level, age, and other factors. Adaptive zone boundaries calibrated to individual baselines would improve personalization.
3. **Limited Validation:** Time constraints precluded extensive validation testing. A rigorous evaluation would require comparison against gold-standard measurement devices and assessment across diverse participant demographics.
4. **Short Session Duration:** Biofeedback training typically requires multiple sessions over weeks to months for sustained benefits. Our single-session demonstrations provided proof-of-concept but not therapeutic outcomes assessment.

Future Enhancements

Potential improvements include:

Hardware Refinements

- Integrate a MAX30102 pulse oximetry sensor for improved PPG signal quality and SpO₂ measurement capability
- Implement a custom PCB design to reduce wiring complexity and improve portability
- Add a rechargeable battery power supply for untethered operation
- Include an OLED display for standalone feedback without computer connection
- Incorporate haptic feedback (vibration motor) for additional modality

Software Improvements

- Implement heart rate variability (HRV) analysis using time-domain and frequency-domain metrics

- Add adaptive zone thresholds based on individual baseline measurements
- Develop session recording and progress tracking functionality
- Create guided breathing exercises with paced visual/audio cues
- Implement wireless data transmission (WiFi/Bluetooth) for remote monitoring or smartphone app integration

Algorithm Enhancements

- Apply advanced digital filtering (e.g., bandpass filters) to improve noise rejection
- Implement motion artifact detection and compensation
- Develop machine learning classifiers for stress state prediction
- Add respiration rate estimation from PPG waveform analysis

User Experience

- Design a more comfortable, wearable sensor form factor
- Create gamification elements to enhance engagement
- Implement progressive training programs with increasing difficulty
- Add social features for group training or competition

CONCLUSION

We successfully developed and demonstrated a functional multi-modal biofeedback system integrating galvanic skin response and heart rate monitoring. The

system effectively provided real-time feedback through visual (LED) and auditory (tonal) modalities, enabling users to observe and modulate their physiological states. Despite technical challenges related to sensor placement and contact maintenance, the system demonstrated the viability of low-cost, accessible biofeedback technology for stress management applications.

The graduated zone-based feedback approach proved intuitive and engaging, while the integration of GSR measurements provided valuable context beyond heart rate alone. This work establishes a foundation for future development of more sophisticated biofeedback devices incorporating advanced signal processing, personalized adaptation, and enhanced user experience features.

Biofeedback technology continues to evolve as sensor miniaturization, computational power, and algorithm sophistication advance. Consumer wellness applications represent a promising domain for translating research insights into practical tools for stress management, performance optimization, and overall wellbeing enhancement.

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