ElStim

Multi-Channel Electrical Stimulation Circuit for Biomedical Applications

ELECOMP Capstone Design Project 2025-2026

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Project Motivation:

Electrical stimulation has emerged as a transformative tool in biomedical engineering, enabling therapeutic interventions for conditions ranging from chronic pain and muscle atrophy to neurological disorders and wound healing. Despite its clinical promise, existing stimulation systems are often bulky, expensive, and limited in channel count or configurability, making them inaccessible for personalized, scalable, or wearable applications.

This capstone project is motivated by the need to develop multi-channel bioelectronic therapy tool through the development of a compact, multi-channel stimulation circuit that is both cost-effective and customizable. By empowering students to design a modular and programmable system, the project bridges engineering fundamentals with real-world healthcare impact.

The initiative aligns with broader trends in digital health, wearable therapeutics, and human-centered design, offering students a chance to contribute meaningfully to the future of biomedical innovation. It also serves as a platform to explore interdisciplinary challenges at the intersection of electronics, physiology, and clinical usability.

Anticipated Best Outcome:

• Functional Prototype: A robust, multi-channel electrical stimulation device capable of delivering safe, programmable biphasic pulses with real-time control over amplitude, frequency, and waveform shape.

• Intelligent Control Interface: A user-friendly software interface (e.g., GUI or mobile app) enabling clinicians or researchers to configure stimulation parameters and monitor system performance.

• Validated Performance: Successful benchtop testing using tissue-mimicking phantoms or simulated biological loads, demonstrating precision, repeatability, and safety under realistic conditions.

• Modular Design Architecture: A scalable hardware and firmware framework that can be adapted for future applications such as wearable neuromodulation, electrotherapy garments, or implantable systems.

• Comprehensive Documentation: Detailed technical report including schematics, PCB layout, firmware code, safety analysis, and clinical relevance, suitable for academic publication or future grant proposals.

Project Details:

Overall system concept: The proposed system is a multi-channel electrical stimulation platform designed to deliver controlled electrical pulses to biological tissue for therapeutic or research applications. It consists of three core subsystems:

1. Stimulation Circuitry

- Each channel includes a programmable current driver capable of delivering biphasic, charge-balanced pulses
- Output parameters, amplitude, frequency, pulse width, and waveform shape, are digitally controlled to ensure precision and safety
- Isolation and protection circuitry such as opto-isolators and current limiters safeguard both the user and the device

2. Embedded Control Unit

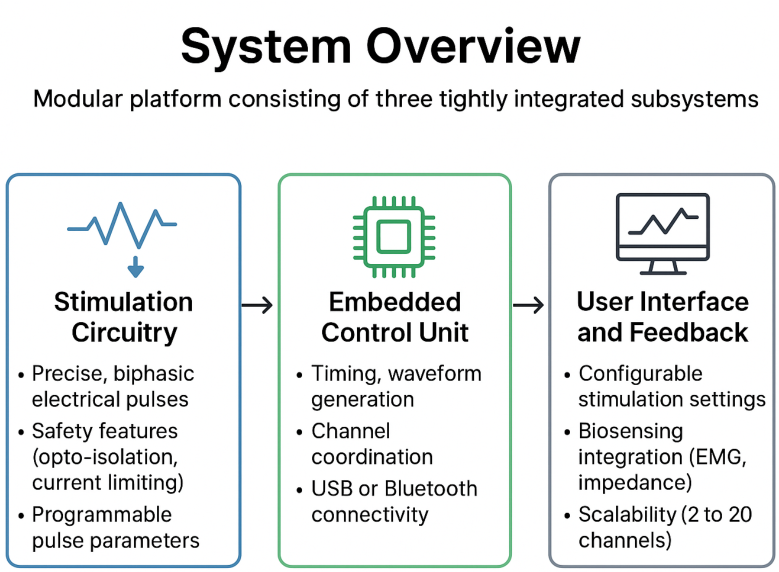
- A microcontroller such as STM32, Arduino, or RP2040 manages real-time signal generation and channel coordination
- Firmware allows dynamic adjustment of stimulation parameters and supports predefined protocols or manual tuning
- Optional integration of Bluetooth or USB for external control and data logging

3. User Interface and Feedback

- A graphical user interface enables clinicians or researchers to configure stimulation settings, monitor output, and save protocols
- Future extensions may include biosensing feedback such as EMG or impedance for closed-loop control or adaptive stimulation
- The system is designed to be modular, allowing easy expansion to more channels or integration with wearable form factors

This architecture supports a wide range of biomedical applications from neuromuscular rehabilitation and pain management to experimental neurophysiology while emphasizing safety, usability, and adaptability. The system is intended to be low-cost and suitable for academic, clinical, or translational research environments.

Block Diagram:



Hardware/Electrical Tasks:

1. Requirements Definition

- Identify stimulation parameters such as voltage, current, pulse width, and frequency range
- Define safety constraints including maximum current per channel and isolation requirements
- Determine the number of stimulation channels and modularity needs

2. Circuit Design

- Design biphasic current driver circuits for each stimulation channel
- Select and configure components including operational amplifiers, digital-to-analog converters, analog switches, and protection diodes
- Implement charge-balancing and current-limiting mechanisms
- Design power supply subsystem, considering dual rails and battery or USB power options

3. Microcontroller Integration

- Select a suitable microcontroller with adequate input-output capabilities and timing precision
- Interface DACs or PWM outputs with stimulation circuitry
- Implement digital control over pulse parameters and channel selection

4. PCB Design and Fabrication

- Create schematic and layout using electronic design automation tools
- Optimize trace routing for signal integrity and safety
- Design modular PCB architecture to support scalability and debugging
- Fabricate and assemble the printed circuit board, including soldering and component testing

5. Testing and Validation

- Conduct electrical testing of each channel using an oscilloscope and dummy loads
- Validate waveform fidelity, timing accuracy, and inter-channel isolation
- Test fault conditions such as short circuits and overloads to verify protection mechanisms
- Perform benchtop stimulation trials on tissue-mimicking phantoms

6. Documentation

- Generate detailed schematics, bill of materials, and PCB layout files
- Document electrical performance metrics and safety compliance
- Prepare user manuals and technical guides for future development or clinical translation

Firmware/Software/Computer Tasks:

1. Requirements Definition

- Define user interaction modes, control parameters, and data logging needs
- Specify timing precision, latency constraints, and real-time responsiveness
- Determine communication protocols for device interfacing and external data exchange

2. Firmware Development

- Program microcontroller to generate stimulation waveforms with configurable parameters
- Implement real-time control over pulse width, amplitude, frequency, and channel selection
- Develop interrupt-driven routines for precise timing and safety monitoring
- Integrate fault detection and recovery mechanisms such as watchdog timers and current sensing
- Enable firmware updates via USB or wireless protocols if applicable

3. Embedded Software Integration

- Interface microcontroller with sensors, DACs, and analog switches
- Implement serial communication protocols such as UART, SPI, or I2C
- Develop modular code architecture for scalability and debugging
- Optimize power management routines and sleep modes for wearable operation

4. Host Software and UI

- Develop desktop or mobile application for device configuration and monitoring
- Implement graphical user interface for real-time control and visualization
- Enable secure data logging, export, and cloud synchronization if needed
- Support user authentication and access control for clinical environments

5. Data Processing and Analysis

- Implement signal preprocessing such as filtering, normalization, and artifact rejection
- Develop algorithms for pattern recognition, anomaly detection, or physiological trend analysis
- Integrate machine learning models if applicable for predictive diagnostics or adaptive stimulation
- Ensure compliance with data privacy standards and encryption protocols

6. Testing and Validation

- Perform unit testing and integration testing of firmware and software modules
- Validate timing accuracy, communication reliability, and user interface responsiveness
- Conduct simulated use-case trials and stress testing under edge conditions
- Document performance benchmarks and failure modes

7. Documentation

- Create detailed code documentation and API references
- Prepare user manuals and developer guides
- Maintain version control and changelogs for collaborative development

Composition of Team:

2 Electrical Engineers & 1-2 Computer Engineers (preference to ELEs who take on CPE tasks)

Skills Required:

Electrical Engineering Skills Required:

- Analog circuit design for biosignal stimulation and filtering
- Digital electronics and microcontroller interfacing
- PCB schematic capture and layout optimization
- Power supply design and low-power system integration
- Embedded firmware development in C/C++
- Signal integrity and noise mitigation techniques
- Serial communication protocols (UART, SPI, I2C)
- Instrumentation and electrical testing with lab equipment
- Safety design for biomedical compliance and fault protection
- Systems integration across hardware, firmware, and software

Computer Engineering Skills Required:

- Embedded systems programming for real-time control
- Firmware architecture design and modular coding practices
- Low-level hardware interfacing (sensors, DACs, switches)
- Serial and wireless communication protocol implementation
- Signal processing and data filtering algorithms
- User interface development for clinical applications
- Secure data logging, encryption, and privacy compliance
- Version control and collaborative software development (e.g., Git)
- System-level debugging across hardware and software layers