ELECTRONIC CONTROL SYSTEMS FOR BIONIC PROSTHESES BASED ON MICROCONTROLLER PLATFORMS

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Abstract*:* this paper presents the design and investigation of an electronic control system for an upper-limb bionic prosthesis based on the STM32 microcontroller platform and electromyographic (EMG) sensors. The proposed system provides acquisition, amplification, filtering, analog-to-digital conversion, and digital processing of muscle bioelectric signals to generate control commands for prosthetic actuators. The hardware architecture, signal conditioning chain, and embedded processing algorithm are described in detail. A multi-channel EMG approach combined with digital signal processing and pattern classification is used to achieve intuitive and reliable control of prosthetic movements. The results show that the integration of electronics, applied mathematics, physics of bioelectric phenomena, and biomedical engineering significantly improves the accuracy, robustness, and usability of bionic prostheses for rehabilitation.

Keywords**:** bionic prosthesis, EMG sensor, STM32, microcontroller, electronic control system, signal processing, rehabilitation engineering.

ЕЛЕКТРОННІ СИСТЕМИ КЕРУВАННЯ БІОНІЧНИМИ ПРОТЕЗАМИ НА ОСНОВІ МІКРОКОНТРОЛЕРНИХ ПЛАТФОРМ

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Анотація**:** у статті представлено розробку та дослідження електронної системи керування біонічним протезом верхньої кінцівки на основі мікроконтролерної платформи STM32 та електроміографічних (ЕМГ) сенсорів. Запропонована система забезпечує зчитування, підсилення, фільтрацію, аналого-цифрове перетворення та цифрову обробку біоелектричних сигналів м’язів для формування керуючих команд приводам протеза. Детально описано апаратну архітектуру, фізичні принципи формування ЕМГ-сигналів та математичні методи їх обробки. Використання багатоканальної сенсорної системи, цифрової обробки сигналів і алгоритмів класифікації рухів дозволяє підвищити точність, надійність та інтуїтивність керування біонічним протезом.

Ключові слова: біонічний протез, ЕМГ-сенсор, STM32, мікроконтролер, електронна система керування, цифрова обробка сигналів, реабілітація.

The increasing number of limb amputations caused by military conflicts, accidents, and chronic diseases has created an urgent demand for advanced bionic prostheses capable of restoring motor functions and improving the quality of life of patients. Unlike passive mechanical prostheses, modern bionic systems rely on electronic control units that form an interface between the human nervous system and electromechanical actuators.

Electromyography (EMG) is one of the most promising control methods because it captures the bioelectric activity generated by muscles during contraction. From a physical point of view, EMG signals represent the superposition of action potentials propagating along muscle fibers, while from a mathematical perspective they can be treated as stochastic non-stationary signals requiring advanced digital processing.

The objective of this study is to develop and investigate an electronic control system for a bionic upper-limb prosthesis using an STM32 microcontroller and multi-channel EMG sensors, integrating electronics, physics, applied mathematics, and biomedical engineering into a unified control architecture.

The proposed electronic control system consists of the following main modules:

- EMG sensor array for muscle signal acquisition;
- Analog front-end (AFE) including instrumentation amplifier and band-pass filter (20–450 Hz);
- STM32 microcontroller with 12-bit ADC and DSP capabilities;
- Digital signal processing block for feature extraction and classification;
- Motor drivers (H-bridges / servo drivers);
- Actuators (servo motors and gear motors);
- Power management unit (Li-ion 18650 battery, charging and 3.3 V regulation).

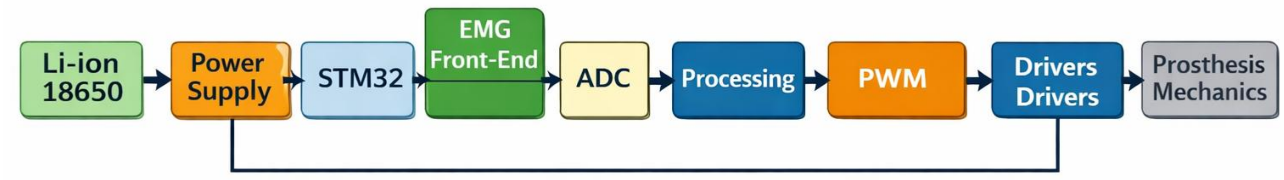

Figure 1 – Block diagram of the electronic control system for a bionic prosthesis.

Figure 1 shows the block diagram of the electronic control system for a bionic prosthesis.

The system is powered by a Li-ion 18650 battery, which provides autonomous operation. The power supply module performs battery charging, protection, and voltage regulation to generate a stable 3.3 V rail for the digital and analog circuits.

The STM32 microcontroller is the central control unit of the system. It manages data acquisition, signal processing, and actuator control. The EMG front-end conditions the bioelectric muscle signals by performing amplification and band-pass filtering (20–450 Hz) to suppress noise and motion artifacts. The conditioned signal is then converted into digital form by the built-in analog-to-digital converter (ADC) of the STM32.

After digitization, the processing block executes digital signal processing algorithms, including feature extraction and movement classification. Based on the recognized muscle activity patterns, the microcontroller generates pulse-width modulation (PWM) control signals. These signals drive the motor drivers, which supply the required current to the actuators.

Finally, the prosthesis mechanics convert the electrical control signals into physical motion, enabling intuitive and natural movements of the bionic hand. The feedback loop ensures stable and reliable operation of the entire electronic control system.

Muscle contraction generates electrical potentials due to ionic currents through the cell membranes. The resulting EMG signal has a very small amplitude (10–500 µV) and is highly susceptible to noise. Therefore, the analog front-end is designed as a low-noise differential amplifier with high common-mode rejection ratio (CMRR) followed by a band-pass filter that suppresses motion artifacts and power-line interference.

The STM32 microcontroller is selected due to its:

- high-speed ARM Cortex-M core,
- integrated 12-bit ADC,
- hardware timers for PWM generation,
- low power consumption,
- suitability for real-time biomedical signal processing.

The EMG signal is digitized at 1–2 kHz sampling frequency and processed using digital filters and feature extraction algorithms.

The following mathematical features are computed:

- Root Mean Square (RMS),
- Mean Absolute Value (MAV),
- Zero Crossing Rate (ZCR),
- Spectral energy (via FFT).

These features form a multidimensional feature vector:

$$F=[RMS,MAV,ZCR,E_{FFT}]$$

A lightweight classifier (k-NN or linear discriminant analysis) is implemented to map EMG patterns to control commands:

$$F \rightarrow \text{Movement class} \in \{grip,release,flexion,rotation\}$$

This approach combines applied mathematics, statistics, and embedded electronics to achieve robust prosthesis control.

The system operates according to the following algorithm:

1. Acquire EMG signals from forearm muscles.
2. Amplify and filter the signal (analog domain).
3. Convert the signal using the STM32 ADC.
4. Perform digital filtering and feature extraction.
5. Classify the movement pattern.
6. Generate PWM control signals for actuators.
7. Execute the prosthetic movement.

This closed-loop architecture ensures fast response and intuitive user interaction.

Table 1 - Comparison of Control Approaches

Control method	**Advantages**	**Disadvantages**
Mechanical	Simple, reliable	No intuitive control
Button-based electronic	Low cost, simple	Unnatural control
EMG-based (proposed)	Intuitive, natural, adaptive	Higher system complexity

Experimental tests show that the multi-channel EMG system achieves high classification accuracy (>90%) for basic hand movements. The use of digital signal processing reduces noise and increases robustness under real operating conditions. The interdisciplinary integration of electronics, physics, mathematics, and biology is crucial for achieving reliable prosthetic control.

CONCLUSIONS. This paper presents an electronic control system for a bionic prosthesis based on the STM32 microcontroller and EMG sensors. The proposed architecture demonstrates that EMG-driven control is an effective and scalable solution for modern rehabilitation devices. Future work will focus on adaptive machine learning algorithms and sensory feedback integration.

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