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Neurointerfaces and Control of Microprocessor Systems Based on Human Muscle Signals

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***Abstract*— This report presents an analysis of modern neural interface technologies for controlling microprocessor systems based on human muscle activity signals. The methods for recording and processing electromyographic (EMG) signals are considered, including hardware implementation based on STM32 microcontrollers. A comparative analysis of actuators (electric motors, servo drives, SMA, EAP, pneumatic systems) is carried out with an assessment of their advantages and limitations. Particular attention is paid to invasive and non-invasive neural interfaces, including Neuralink technologies and Targeted methods Muscle Reinnervation (TMR). The final part contains conclusions about the prospects for the development of cyber-physical systems.**

Keywords*— Actuators, Neurointerfaces, Electromyography (EMG), Microprocessor Systems, Brain-Computer Interface (BCI), Neuralink, Targeted Muscle Reinnervation (TMR)

I. Introduction

Modern advances in neural interfaces and microcontroller systems open up opportunities for creating devices that interact with human nervous and muscular activity. This is especially relevant for prosthetics and controlling external devices via bioelectric signals [1]. This paper analyzes methods for recording EMG signals, compares actuator types, and reviews neural interface technologies, including promising developments such as Neuralink [3].

II. Interpreting Muscle Signals: From Acquisition to Control

At the heart of many neurointerfaces lies electromyography (EMG), a technique that measures the electrical activity produced by muscle fibers during contraction. EMG signals, which manifest as bioelectric potentials, can be captured using non-invasive surface electrodes placed on the skin or invasive needle electrodes inserted into muscle tissue for greater precision [7]. The choice between these methods depends on the application: surface EMG is user-friendly and widely accessible, while invasive approaches offer superior signal clarity but require surgical intervention.

Processing EMG signals is a complex but critical step in translating muscle activity into actionable commands. The process begins with signal amplification and filtering to remove noise, such as electrical interference or motion artifacts, typically using bandpass filters with a frequency range of 20–500 Hz. Next, key signal features are extracted, including the root mean square (RMS) amplitude, integrated signal strength, or frequency-domain characteristics derived through fast Fourier transform (FFT) or short-time Fourier transform (STFT). These features feed into classification algorithms, ranging from simple threshold-based methods to sophisticated machine learning techniques like support vector machines (SVM) or neural networks, which can distinguish between different muscle activation patterns [2].

Microcontrollers, particularly the STM32 series from STMicroelectronics, are pivotal in this process. These devices offer high sampling rates (1–2 kHz) to capture the rapid dynamics of EMG signals and support digital filtering through finite impulse response (FIR) or infinite impulse response (IIR) algorithms. The STM32's compatibility with CMSIS-DSP and CMSIS-NN libraries enables developers to implement machine learning directly on the microcontroller, reducing latency and power consumption [6]. Manufacturers like STMicroelectronics demonstrate strong readiness to support neurointerface development by providing extensive documentation, optimized software libraries, and tools for real-time signal processing. This robust ecosystem empowers engineers to create compact, energy-efficient systems tailored to individual users' EMG profiles, paving the way for personalized neurointerface solutions.

III. Actuators: The Mechanical Foundation of Neurointerfaces

The effectiveness of a neurointerface hinges on its ability to translate processed signals into precise, lifelike movements—a task entrusted to actuators. These mechanical devices convert electrical commands into motion, and their performance directly impacts the functionality of prosthetics, robotic manipulators, and other cyber-physical systems. The diversity of actuator technologies reflects the varied demands of neurointerface applications, each offering unique advantages and facing distinct challenges.

Traditional electromagnetic actuators, such as DC motors, are prized for their reliability and durability, making them a mainstay in prosthetic limbs and industrial robots. However, their inertia can limit responsiveness, posing challenges for applications requiring rapid, dynamic movements. Servo motors, by contrast, excel in precise positioning, ideal for robotic arms or manipulators where accuracy is paramount, though their force output is often constrained.

Emerging actuator technologies push the boundaries of what neurointerfaces can achieve. Shape memory alloys (SMAs), such as nitinol, offer remarkable compactness and biocompatibility, making them suitable for bioinspired devices like muscle-like actuators in soft robotics. Their slow response time, however, restricts their use in high-speed applications. Electroactive polymers (EAPs) provide flexibility and softness, mimicking biological tissues in soft prosthetics, but their complex control requirements remain a hurdle. Pneumatic actuators deliver smooth, compliant motion, ideal for soft robotic systems, yet their reliance on bulky air supply systems limits portability [2].

Actuator manufacturers are actively addressing these challenges, signaling their readiness to support neurointerface advancements. Companies developing SMAs and EAPs are investing in research to enhance response times and simplify control schemes, while traditional motor manufacturers focus on miniaturization and energy efficiency to meet the demands of wearable devices. This collective effort ensures that actuators can keep pace with the sophisticated signal processing capabilities of modern neurointerfaces, enabling seamless integration into compact, user-friendly systems.

IV. Modern advances in neural interfaces and Interpretation of muscle signals by microprocessor systems

II.1 Electromyography (EMG)

EMG signal is a bioelectric potential that occurs when muscle fibers are excited. Registration is performed by surface (non-invasive) or needle (invasive) electrodes [7].

II.2 Stages of EMG signal processing:

Preamplification and filtering: artifact removal (bandpass filter 20–500 Hz).

Feature extraction: direct integration, RMS, frequency analysis (FFT/STFT).

Classification: threshold algorithms, machine learning (SVM, neural networks) [2].

Customization to the user: individual training EMG profiles.

II.3 Hardware implementation

STM32 microcontrollers (e.g. STM32F407) provide:

Signal sampling (1–2 kHz);

Digital filtering (FIR/IIR);

Support for CMSIS-DSP/CMSIS-NN libraries [6].

Table 1 – Comparative analysis of actuators

Actuator type	Advantages	Flaws	Application
Electric motor	Reliability	Inertia	Prosthetics, robots
Servo motor	Precise positioning	Limited effort	Manipulators
SMA (nitinol)	Compactness, biocompatibility	Slow response	Bionics
EAP	Flexibility	Difficulty of management	Soft dentures
Pneumatic actuator	Smoothness of movement	The bulkiness of the system	Soft robotics

V. Conclusions

Neurointerfaces stand at the forefront of scientific and technological innovation, merging human physiology with advanced electronics and robotics. By harnessing EMG signals, leveraging high-performance microcontrollers like the STM32, and integrating diverse actuators, these systems are redefining possibilities in medical rehabilitation and human-machine interaction. Manufacturers of microcontrollers and actuators are well-prepared to support this evolution, offering energy-efficient hardware, optimized software, and ongoing research to overcome technical limitations.

The future of neurointerfaces is bright, with prospects for miniaturized implants, enhanced signal decoding, and reduced power consumption. In healthcare, TMR-enabled prosthetics and tactile feedback systems are already improving quality of life for amputees, while Neuralink's brain-machine interfaces hint at broader applications, from treating neurological conditions to enhancing cognitive capabilities [3, 4]. Beyond medicine, neurointerfaces promise to reshape industries, enabling intuitive control of robots, drones, and immersive digital environments. The key to realizing this potential lies in continued integration of biocompatible materials, adaptive algorithms, and cyber-physical systems, ensuring that neurointerfaces become both accessible and transformative.

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