Development of an Electronic Circuit for Active Amplification of EMG Signals Using Dry Electrodes

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Abstract *— This manuscript describes the development of a circuit for amplifying surface EMG with a high input impedance, designed to control bionic limb prostheses. A peculiarity of using bionic prostheses to control upper and lower limbs is the presence of a high impedance of contact with the skin, while the equality of resistances in both signal lines is not guaranteed, which is due to dryness of the skin. Patients need to be comfortable with bionic prostheses on a daily basis and eliminate the need for special treatment of the stump. The authors present a developed circuit with additional buffering of input signals, the right leg driver circuit, a band-stop filter, and a band pass filter stagger. A software does the control of amplification at the circuit by using a digital potentiometer in the feedback of the output amplifier. The signal is digitized directly on the amplifier board to reduce the effect of noise on analog lines. The authors achieved a noise value of 20 µV (peak-to-peak) at direct skin contact.*

Keywords — *electromyography, biosignal amplifier, active dry electrode, bionic prosthesis control system.*

INTRODUCTION

At present, a 2-electrode circuit is traditionally used to control either bionic prostheses, which allows 2 discrete commands to be reliably selected or 1 proportional.

The processing of the EMG signal in prostheses is simplified by subjecting the negative part of the original signal to inversion and repeated filtering to obtain simpler forms - envelopes that carry information only about the fact of muscle tension, but not about the intensity, as a result of which informative features important for pattern recognition are lost - wave-like signals similar in shape to an ECG with a pronounced zero level. At the same time, the inverted (taken in modulus) signal does not even have an average level, which allows only detecting the excess of the threshold and the rate of rise of the front.

Another factor of the lack of control channels is the excessive number of controlled degrees of freedom.

The bionic hand module may have up to 8 drives for controlled degrees of freedom, and when using traditional prosthetics control schemes, the user is deprived of the possibility of direct control of each individual driving element.

Control of complexly combined movements of the prosthesis (pattern, gesture) is used worldwide at a limited number of control channels. Thus, a bionic hand with 5 (five) fingers with independent electric drives is set in motion with just one command (open/close). In this case, the trajectories of movement of individual fingers are preset using special movement patterns. The object of control in this case is the dependence of the fingers' position in time during the execution of the selected pattern.

The input signal to control the prosthesis by means of electromyogram can be the following options:

1. Discrete command (1 or 0 - on/off) generated by the recognition system based on the simplest comparison of the EMG amplitude value and a given threshold level
2. The proportional command is the result of complex processing of an electromyogram to detect the force of muscle contraction.

The interaction of a patient with a prosthesis is carried out by processing a superficial electromyogram [1-5] from residual muscle groups, while it is possible to classify complex combinations of activation of a group of several muscles, which makes it possible to identify additional control channels (gestures) that can be used to quickly switch between several prosthesis gestures without the need to use special keys on the prosthesis body.

The amplitude of the muscle activity signal recorded by surface electromyography is in the range of 0.1–5.0 mV [6–7], and the frequency band is in the range of 10–500 Hz. Thus, common mode interference from public networks at 50Hz (60Hz in some countries) affects the wanted signal.

Studies [8] on the analysis of EMG signals, as a rule, use (a pair for each recording channel) either disposable contact electrodes or reusable using conductive gels that provide a low impedance of contact with the skin. Ensuring the equality of the impedance of both contacts is one of the most important factors affecting the quality of the received biosignals (both for EMG and for ECG and EEG). This is due to the influence of the imbalance of skin contact resistances on the input signal levels of the amplifier, for example, the difference in input impedances of more than 50 KΩ is already critical [9], in this case, it is recommended to take additional measures to prepare the subject's skin: shaving the hairline and moisturizing, in including, using conductive gels.

In order to increase the efficiency of common-mode noise suppression, a so-called Right-Leg Driver circuit is added to the amplifier's input stage [10-17], the name of which is associated with early studies on ECG recording, and the subject's right leg is the most distant place on the body from the place of biopotential registration. The addition of the Right-Leg Driver provides a significant improvement in the Common-mode Rejection Ratio by buffering the common-mode noise signal with phase inversion and connecting it back to the user's body. The disadvantages of the presented circuits are the influence of impedance imbalance in the input differential lines on the quality of suppression of common-mode interference, which requires additional moisturizing of the skin area, or the use of disposable "wet" electrodes.

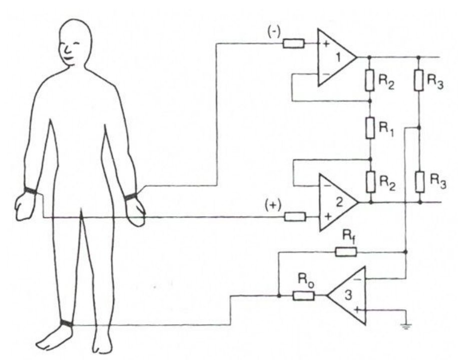

Fig. 1: A typical scheme of Right Leg Driver

METHODOLOGY

The specificity of using surface electromyography in the management of prostheses lies in the impossibility of using the traditional approach with wet electrodes. Contact with dry or insufficiently hydrated skin has a high resistance, up to megaΩ units.

Despite the high differential impedance of the instrumentation amplifiers due to the buffering of the input staggers inside the microcircuit, to ensure the stable operation of the instrumentation amplifier, it is necessary to ensure the drainage of the reverse bias current, for which, with a unipolar power supply, the inputs are pulled up to the reference voltage (usually equal to half the supply voltage), with a bipolar food - to the ground. However, this reduces the input impedance of the instrumentation amplifier by several orders of magnitude and becomes equal to the resistance of the pull-up resistors.

Because of the analysis of works [18-20], it was decided to introduce additional preliminary buffering of signals from the electrodes. For this, a voltage follower circuit was used, which is implemented using an operational amplifier connected in a non-inverting circuit. At the same time, in order to preserve the negative part of the input signal, the power supply circuits of the buffers are switched on in a bipolar circuit.

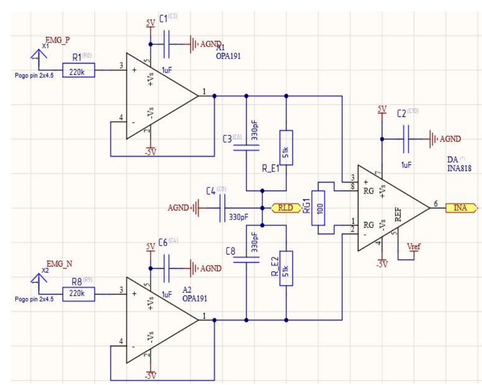

Fig. 2: High impedance amplifier input stagger

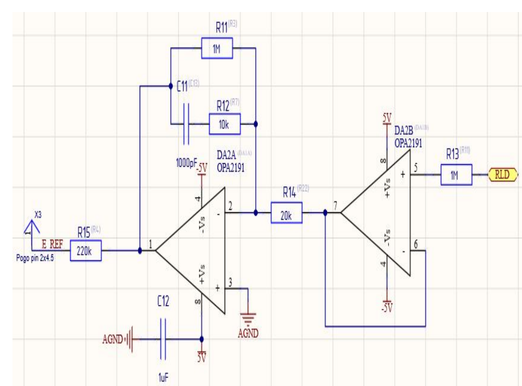

Fig. 3: Right Leg Driver circuit

A feature of amplifiers used for recording low-voltage signals (EMG, ECG and EEG) is the influence of pickups from public electrical networks (220V@50Hz). To suppress them, as a rule, an active stagger of band-stop filters [21], tuned to the required frequency, is used.

In addition to the right foot driver, a Twin-T auxiliary band-stop filter was installed at the output of the instrumentation amplifier and tuned to 50 Hz (60 Hz also possible).

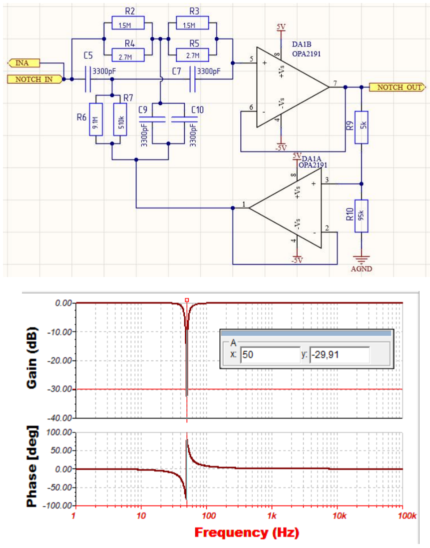

Fig. 4: 50 Hz band-stop filter, amplitude frequency response/phase-frequency response

The EMG signal bandwidth is in the range from 10 to 1000 Hz [22]. The use of a high-pass filter (HPF) with a cutoff band of 10 Hz allows you to cut off the unwanted influence of extraneous components caused by ECG and hand movement artifacts. An additional effect of HPF is the elimination of constant components in the intermediate signal, which could significantly limit the dynamic gain range.

A low-pass filter with a cut-off frequency of 2000 Hz eliminates the influence of high-frequency interference.

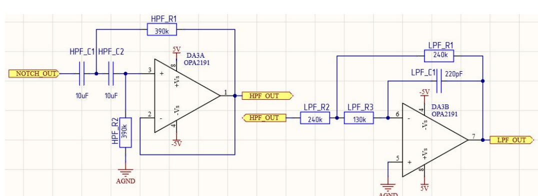

Fig. 5: Amplifier input stage with high Impedance HPF and LPF filter stagger circuit

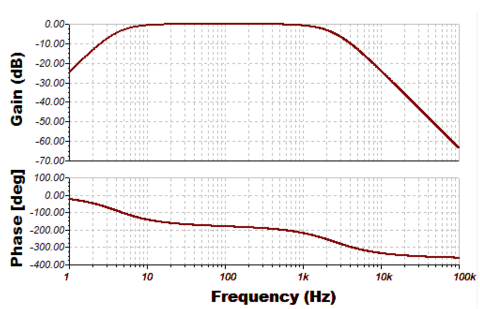

Fig. 6: Amplitude frequency response/phase-frequency response of the HPF and LPF stagger

When adjusting the prosthesis, as a rule, the prosthetist performs manual adjustment of the EMG amplification level by rotating a mechanical potentiometer built into the amplifier board [23]. To automate the tuning process and the possibility of automatic gain control, the authors added a digital potentiometer MCP4161 to the output amplification stagger [21].

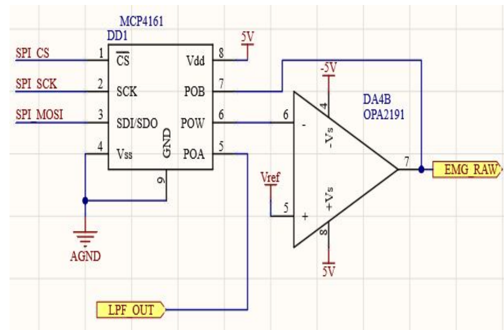

Fig. 7: Schematic of the output stagger of amplification with software switching of the gain control

The overall circuit gain is calculated using the formula:

$$K = K_{BUF} \cdot K_{INA} \cdot K_{NOTCH} \cdot K_{HPF} \cdot K_{LPF} \cdot K_{AMP}$$

The gain K_{INA} is determined by the expression

$$K_{INA} = 1 + \frac{50000}{RG}$$

RG – is the resistance in the feedback circuit is equal to 100Ω. $K_{INA} = 501$

The gains of the band-stop, LPF and HPF filters equal to 1. $K_{NOTCH} = K_{HPF} = K_{LPF} = 1$

The gain control of the output stagger K_{AMP} is defined as $K_{AMP} = \frac{Rbw}{Rwa} = \frac{CMD}{257-CMD}$

Where CMD is the control word setting the resistance of the potentiometer, range of values from 0 to 257.

Thus, the final gain depends on the value of the control word and is expressed as $K = \frac{501 * CMD}{257-CMD}$, the dynamic range of the gain is from x1.957 (5.8 dB) to x128256 (102 dB).

The output signal of the analog part of the electrode is a bipolar signal, symmetrical about the zero average level (in this work, a 2.5V reference is used). To implement the chosen concept of a digital electrode and reduce the influence of external electromagnetic fields on the analog signal transmission lines, it was decided to select an ADC microcircuit for installation directly on the electrode board (MRB). ADS8866[25] became a suitable chip (see Table).

TABLE I. ADC ADS8866 PARAMETERS

No.	Parameter	Value
1	Capacity	16 bit
2	Maximum performance	100,000 conversions/sec
3	Supply voltage for digital circuits	1.65…3.6 V
4	Supply voltage for analog circuits	2.7…3.6 V
5	Reference voltage	2.5…5 V
6	Intake power	0.7 mW at 100 conversions/sec 0.07 mW at 10,000 conversions/sec
7	Dimensions	3x3 mm

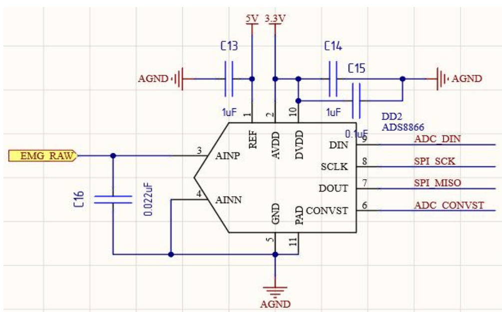

Fig. 8: Analog-to-digital conversion circuit

When choosing a microprocessor, the main criteria are the frequency of operation and the amount of available RAM. In order to receive data from 8 electrodes, it is necessary to perform software buffering of signals. The optimal solution turned out to be the STM32F413RG microprocessor [26], made according to the Cortex-M4 architecture and having the largest RAM size in its segment.

Main characteristics:

- Frequency: up to 100 MHz
- SRAM: 320 Kbyte
- Flash: 1 Mbyte
- Floating point unit

The same SPI module is used to exchange data with ADC microcircuits and digital potentiometers, and auxiliary signals CS (Chip Select) are used for device dispatching, connection to active electrodes is carried out using 10 pin FFC cables with a contact pitch of 0.5 mm.

Data exchange with external devices (including with bionic prostheses) is carried out through three interfaces:

- Bluetooth BLE (implemented using the BGM113 module)
- RS-232 (direct connection to the microprocessor)
- CAN (implemented using the TCAN335 front-end chip)

RESULTS

Because of the research carried out, electrical circuits of two devices were developed:

1. Active digital electrode module
2. Microprocessor-based module for capturing signals from digital electrodes. Up to 8 modules are supported.

The implemented functionality of the active digital electrode:

1. Additional signal buffering for high input impedance
2. Differential amplification of signals from electrodes placed on the user's skin
3. Maintaining the original waveform relative to the zero level (2.5 V)
4. Active low-pass filter (LPF)
5. Active high-pass filter (HPF)
6. 50 Hz band-stop filter
7. Programmable gain adjustment

Photos of the manufactured module samples are presented on Fig. 9 and Fig. 10.

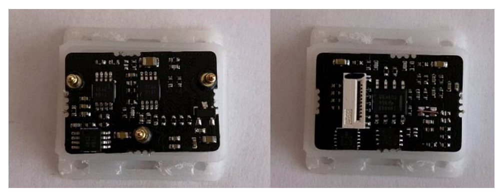

Fig. 9: Active digital electrode appearance

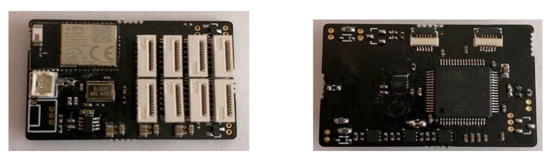

Fig. 10: Appearance of the microprocessor module for connecting up to 8 active electrodes

Samples of EMG signals recorded from the subject's forearm are shown in Fig. 11 - Fig. 13.

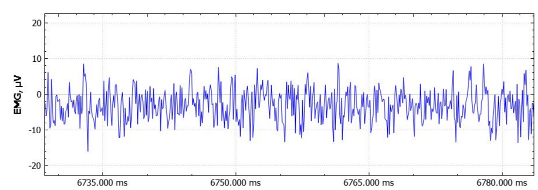

Fig. 11: Noise level for skin contact and relaxed muscles is about 20 uV (peak-to-peak)

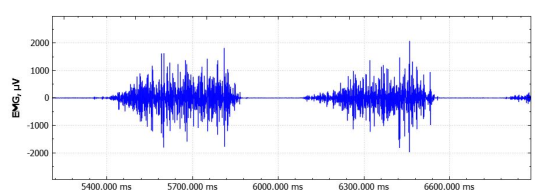

Fig. 12: An example of a recorded EMG signal

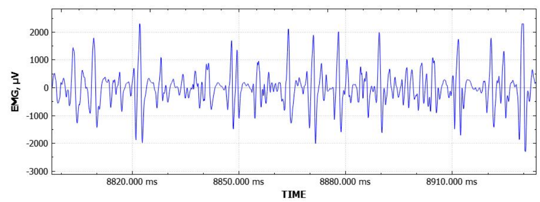

Fig. 13: An example of a recorded EMG signal

DISCUSSION

The developed active digital electrodes provide protection against external interference and pickup of power grids, including, this can allow you to reliably control the prosthesis and protect yourself from false alarms when the user is in public electric transport (metro, electric train, tram, trolleybus), because manufacturers of modern prostheses do not recommend using them in such modes of transport.

The biopotential registration module implements differential amplification of input signals from skin electrodes with a level of common mode noise suppression of up to 140dB, additional active suppression of line noise 50Hz (60Hz) by 30dB, an active upper filter (to remove artifacts caused by hand movement and the user's heartbeat) and an active filter low frequencies to eliminate high frequency interference. A feature of the module is the absence of signal conversion in modulus, which is typical of electrodes used in all prostheses on the market. As a rule, in them the signal is converted modulo and pre-filtered, so that the original signal form undergoes irreversible changes. This, on the one hand, makes it possible to simplify signal detection by simply adjusting the triggering threshold, however, it makes it impossible to recognize and isolate patterns of motor activity. The developed module implements the traditional approach for signal preprocessing, the purpose of which is to preserve the original waveform without deformation, while significantly reducing the level of interference. A signal with a pronounced zero level is obtained at the output of the module.

CONCLUSION

The authors managed to significantly reduce the effect of the imbalance of the input impedances in the input channels of the amplifier by means of additional buffering, which also made it possible to achieve a high sensitivity of the amplification circuit with a low noise level at a level of no more than 20 uV peak-to-peak in direct contact with the subject's skin.

It is possible to chain an arbitrary number of electrodes (from 1 to 8) to capture signals from distributed muscle groups. The use of more than 2 electrodes allows for allocating additional control channels due to the implementation of recognition algorithms for individual user gestures.

The developed module for multichannel registration and processing of biopotentials consists of a microprocessor module and a set (up to 8 pieces) of active dry electrodes connected to it, which provide reliable registration of biosignals, even with insufficient quality skin-electrode contact and can be used for implementation

1) EMG control system for bionic prostheses of the upper and lower limbs

2) Personal portable electrocardiograph for early diagnosis and prediction of crisis situations of the patient's cardiovascular system

4) Human-machine interaction interface based on EMG or EEG processing

ACKNOWLEDGMENT

This research has been financially supported by the Ministry of Science and Higher Education of the Russian Federation under the grant agreement No. 14.577.21.0290 of 28 November 2018. The grant has been provided to perform the applied research on the topic: "Development of domestic line of robotic bionic prostheses of upper limbs, providing performance options taking into account different degrees of arm amputation, using myoelectric intelligent grip control and providing a level of functionality close to a healthy human hand" (unique identifier RFMEFI57718X0290). Work on the project has been carried out at the Moscow Polytechnic University.

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