Prosthesis Control System of the Upper Limb

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Abstract—**This paper overviews developing process of a prosthesis control system using electromyographic signal. Corresponding hardware and software solutions are suggested. In a nutshell described significant achievements in the field of prosthetics and the main ways to control such devices. The complexity of the implementation of prosthetic devices based on these principles are considered.**

I. Introduction

A rough estimation of the world amputee population can be made using some references from different sources online, according to an article from the free of charge website advanceamputees.com well over two million Americans have suffer from an accident or disease that caused them a limb amputation and the number to 2050 is estimated to be around 3.6 million people. [1] Worldwide the number of amputees was around 10 million people in 2008 [2] and from this 30% consist of upper limb amputees. This number is divided according to the amputation level like follows: 59% below elbow amputations, 28% above elbow and elbow disarticulation amputations, 8% elbow amputations and 5% hand/wrist amputations. This can be better observed in Fig. 1.

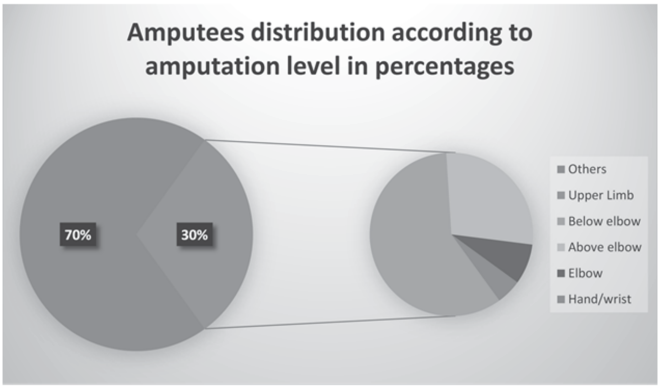

Fig. 1. Amputee distribution in percentages according to data from Stanford university's class in prosthetics [2]

Statistics show that this number is estimated to double by 2050. From this we can conclude in the importance of prosthetics and orthotics in medicine and life in general to patients and their families regardless of the motive behind the amputation.

In the field of prosthetics there are many ways of classification, in general and of most regular use they are classified depending on the amputation level (as seen before), or the type of control and depending on the construction, the biological object to replace and the moment of replacement. Depending on the drive method, mechanical, electrical and electro-mechanical prosthetics can be found. Prostheses can also be postoperative, initial, preparatory, definitive, and for special-purpose. Early amputees usually become depressed, angry, disappointed or withdrawn and therefore the psychological purpose of prostheses is important to give the amputee a sensation of commodity and wellbeing as well as the perception or regaining of their natural functional lives. Patients are usually given a post-operative prosthesis immediately after the surgical procedure (if they meet certain parameters and requirements). Once the sutures are removed the latter is changed for an initial prosthesis, these devices are meant to be worn for the first few weeks of after amputation, until the suture line is stable and the skin can tolerate the stresses of more intimate fitting. Preparatory prostheses are used during the first few months of the patient's rehabilitation for a period no longer than 6 months and their purpose is to ease the transition to a more definitive device. After the patient's residual limb has stabilized to ensure fitting for as long as possible, a definitive prosthesis is prescribed. This is not a *definitive* device since any mechanical device is subject to wearing and with time will not perform as desired. A certain number of patients will require a prosthesis that allows them to realize a special activity, and hence a special purpose prosthesis is required. This can provide with some grappling function or special moves that general purpose prostheses do not possess.

Biologists and physicists are concerned with the problem of real restoring lost functions of the human body. The most preferable is to create necessary organ «in vitro». In this way, it would have had the same features as the original. But 3D printing technology of human organs have just appeared and is not widespread yet (studies of biochemical processes, and methods of forming organic fabrics are still ongoing). The process of creating an organ is very complicated. Today, it is much easier (though not effectively enough) to replace the lost organ with the physical substitute, rather than biological. Especially when it comes to the limbs. But in this case we also have to face some challenges which cannot be completely solved.

This paper is to show another one attempt to create the basis of the upper limb prosthetic and its management system. Highlighting the main steps of layout design of such system we will point problems which impose limitations on the designing process.

II. WAYS TO GET INFORMATION ABOUT MANAGING

Upper limb, i.e. hand, is the executive part of the body. All movement information is generated in the brain structures. Then, an electrical impulse is transmitted along nerve fibers to the alpha motor neurons located in the spinal nerve and excite them. In response, the alpha motor neurons generate stimulating muscle contraction. Their axons act as conductors of these impulses - they directly connect skeletal muscle fibers to neuron bodies. Theoretically, the electrodes can be connected to any area of the impulse transmission and get the signal. In practice, it is much more difficult.

A. The use of neural structures

1) Brain: For a long time, scientists from the University of Pittsburgh have been researching the functioning of the cerebral hemispheres in order to describe the way of acting of nerve cells in the process of performing a variety of movements. The obtained results allowed to start the development of brain-computer interface (BCI). Not so long ago the first tests were carried out. Using the interface was implemented the control of anthropomorphic arm prosthetic with 7 degrees of freedom. A patient with limb paralysis have been able to successfully carry out all the necessary actions.

This is an example of successful use of electrical brain signals to control a robotic arm. The system consists of two main components: the electrodes and the algorithm. Electrode designing is quite complex (similar to those which shown in Fig. 2). In fact, there is not one electrode and an array of several dozen micro needles at the ends of which the pads are located. The electrode is implanted in the part of the cerebral cortex, where skeletal muscle control neurons are concentrated. The algorithm of processing of the electrical signal involves the calculation of the direction vector of the motion, which the patient sets to his limb. When the host of TV show «60 minutes» asked Jan Scheuermann (patient) what we have to do to control the prosthesis she said that it as if it happens automatically.

2) Peripheral nervous system: Using peripheral nerves also requires special electrodes implantation. However, it is much safer for the patient than implantation in the cerebral cortex. In addition to using needle electrodes can be used so-called mesh electrodes (creating of array of metallized holes on the base of bioinert material, through which axonal sprouting takes place) [3]. The smaller holes are, the more available axons are (hence the greater number of motor units). The processing algorithm may be similar to the processing of the electromyogram (EMG).

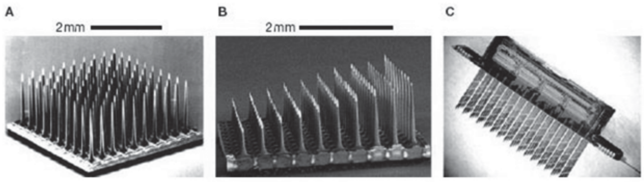

Fig. 2. Different types of the electrode arrays. (A) The Utah Electrode Array (UEA). (B) The Utah Slanted Electrode Array (USEA). (C) – (A)-type with active electronics [4]

Prototype prosthetic hand with this type of control still does not exist, and, first and foremost, this is due to the complexity of the production of mesh electrodes.

3) The use of skeletal muscle: The smallest functional unit of the contractile apparatus is a motor unit. It includes motoneuron, its axon and group of muscle fibers. The number of muscle fibers can range from tens to hundreds [5]. All of them contract simultaneously. Due to electrical muscle activity a signal with amplitude which ranges from tens to thousands mV is generated. This fact allows to record it from surface of the body.

Prostheses using muscle signals as a source of information for the management are the most common. They are easy to make as well as algorithms are not complex. Such systems do not provide the flexibility of movement. Their main purpose - to be able to perform simple actions (e.g., clenching/ unclamping the hand and grabbing with two fingers). The greatest success in the development of described devices have two companies: RSLSteeper (bebionic) [6] and Touch Bionics (i-limb [7] when amputation is at forearm level and i-digits when amputation of the hand takes place) (Fig. 3).

Comparing the i-limb and bebionic, we cannot say that one is definitely better then another. Both have a set of movement patterns, both use two sensors, made of light and strong metals and plastics, both have unusual appearance. Speaking of the i-limb, we should mention the mobile app which allows to quickly adjust the prosthesis as needed and grip chips technology. Grip chips involves placing special devices in required for patient places (next to the organizer, computer keyboards, etc.). While a person approaching to these devices, the prosthesis through a wireless connection with them will automatically change the motor pattern.

Fig. 3. Bebionic (left picture), i-digits (in the center) и i-limb (right picture)

Also, people from Rehabilitation Institute of Chicago, with the support of the agency DARPA have attempted to design the prosthesis on the base of electrodes implanted in the muscle. In the short video it was shown as a man with arm amputation at shoulder level is able to take the cup, lift a tennis ball from the floor and catch a falling handkerchief without any help [8].

B. Control mode selection

It is better to begin with simple things. Therefore, it was decided to develop a type of system controlling with a relay (when the input force is not important, the main thing that the threshold is exceeded) based on receiving information from skeletal muscle. It is easier because:

- Metal plates from conductive bioinert alloys or metals are suitable as the electrodes (at the stage of research - even electrodes used in electrocardiography).
- Algorithm should calculate only the angle of rotation of the mechanical parts.
- The availability of the necessary materials and components.
- Despite the simplicity, this prosthesis can facilitate everyday activities.

III. Designing model for management system

After research it became clear which EMG signal processing stages perform better in analog form and which – in digital. Denote them:

- A high-pass filter is needed in the instrumentation amplifier circuit (basing on a reference design provided by chip developers).
- It is necessary to carry out bias of the contour line in analog form.
- It is more effectively to rectify and smooth signal with the help of software.

This approach will reduce the size of analog circuit while microcontroller will not have to perform excess computations. Now, let's turn to the consideration of the analog and digital parts of the layout.

A. The analog part

To record signals from the human's body at least a simple circuit is needed. There are a lot of information how to do this in medical electronics books, datasheets and just in the Internet (you can find a variety of electrical circuits for biopotentials registration). There are different versions: with the filters, without filters, with rectifiers, with smoothing filter. It was decided to use only the most necessary things such as instrumentation amplifier (IA), a high-pass filter (HPF), amplifier and bias circuit. IA is connected as recommended to virtual ground (to reduce common mode noise) and to HPF with a 10 Hz cut-off frequency. HPF consists of low pass filter (LPF) made from the operational amplifier U1A, the output of which is connected to the reference input of the IA. HPF input is connected to the output of the IA. The electrical circuit of this part is shown in Fig. 4 and Fig.5.

Firstly, RC-circuit consisting of a resistor R9 and capacitor C3 with a 2 kHz cut-off frequency is an anti-aliasing filter. The output OUT is connected to the ADC built-in into the microcontroller. Secondly, it is a LPF that eliminates high frequency noise. The fact that such a filter has a sloping characteristic slightly distorts the signal. It is enough for controlling. Such a large cut-off frequency is chosen with a view to capture the useful part of the spectrum of the EMG signal accurately. Main power spectrum ranges from 50 to 200 Hz. However, most researchers agree that below 20 Hz and above 1500 Hz there are no useful parts of EMG spectrum [10].

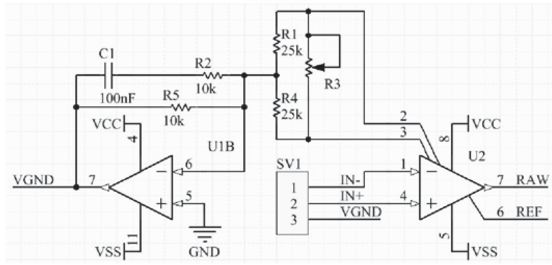

Fig. 4. Instrumentation amplifier connected to virtual ground.

It is recommended to amplify signal in two stages. Primary amplification is provided by IA. Gain K1 is adjusted by the resistor R3. Since the amplitude of the signal varies from person to person the variable resistance of 1 ohm is required. Thus, it is possible to ensure gain of few thousand. The output amplifier is an inverting one. Its gain K2 is also variable. The gain changing by resistance R6 (Fig. 6). Inversion of the signal does not degrade signal (in stages of digital signal processing it is rectified).

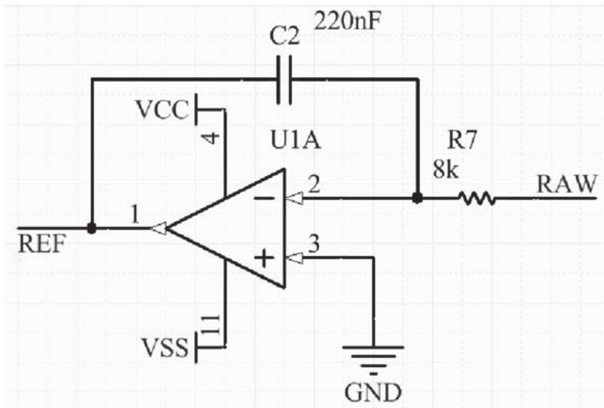

Fig. 5. Noise reduction and isolation circuit

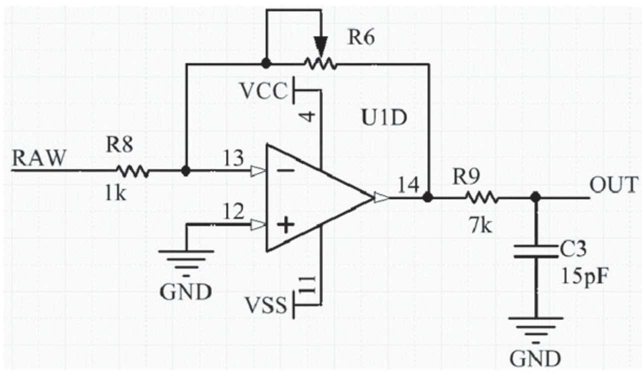

Fig. 6. Output amplifier and anti-aliasing filter

EMG signal contains as area of positive voltage and negative one. Thus, if the bottom level of the circuit power supply and virtual ground are united approximately a half of the useful signal power will be lost. An unipolar to bipolar power supply converter could be used to solve this problem. Then the voltage at the VCC and VSS outputs will be +2.5 and -2.5 V (when powered by 5 V), respectively, and at the GND - 0 V. To do the same with lower costs we can use splitting supply circuit (Fig. 7). Mid-span power is selecting by the (resistors R10 and R11). The amplifier is used as a voltage regulator.

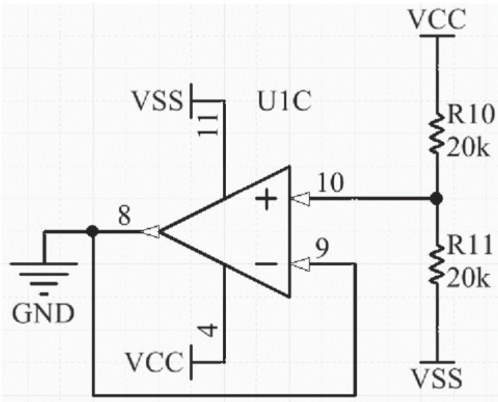

Fig. 7. Splitting supply circuit

Now the circuit is done. As IA is suitable AD8221, the use of quad operational amplifier TL064 could reduce board space. All that is left to do - to apply the electrodes to the patient's skin, connect them to outputs of the SV1 connector (Fig. 4) and to power the circuit. At the output (labeled OUT) there is the EMG signal shifted by +2.5 V passed through band-pass filter and amplified in the K1*K2 times. The ADC can be connected now.

B. *The digital part*

For rapid prototyping, it was decided to use the Launch Pad Development Kit from Texas Instruments (TI) based on the FR5969 microcontroller. Built-in 16 MHz clock provides the necessary computational resources for at least two channels. Reduced power consumption of such TI microcontrollers is also very useful.

To program the microcontroller we need to choose three ADC channels (two channels for EMG signal and one for GND bias), 12-bit resolution. The necessary sampling rate is equal to 4000 Hz. Put electrodes on the short head of the biceps and the short head of the triceps (the test was performed on a healthy person). Run the microcontroller and set the gain.

With help of our own terminal program resulting curves can be displayed on the PC screen (Fig. 8). The top curve - EMG of the triceps, lower – of the biceps. The bias was removed from signal before displaying on the PC. The biceps signal is just below zero. This is because each analog signal processing board has its own offset. Here one offset is used for both channels. Now, when the system for recording EMG signal is designed, signal processing can be made.

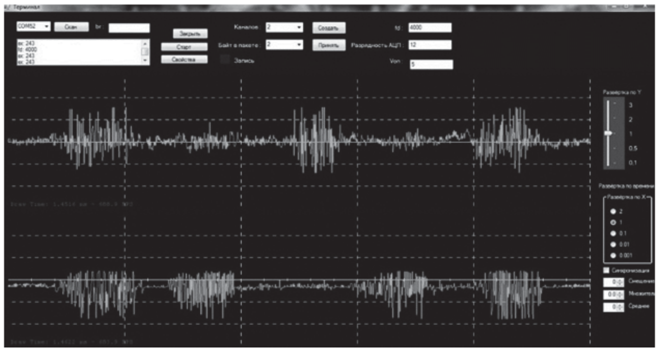

Fig. 8. The electromyogram signal

C. *Digital processing*

Using the original EMG signal to control the prosthesis is possible with some complements (threshold and delay) but is not enough reliable. Therefore, before using the threshold, primary processing is made.

Fig. 9 shows a signal processing algorithm. At each iteration we get the point of the EMG signal with a constant shift of +2.5 V. This constant does not include useful information and should be deleted. To do it, it is necessary to know its value. For this, we used a third ADC channel. Then, the sample of GND signal is deleted from sample of EMG signal, so the EMG signal with respect to zero is only left.

To avoid losing signal power when smoothing it is fully converted to positive part. Smoothing is performed via 2 order IIR digital LPF with a 2 Hz cut-off frequency and averaged over 50 samples. After that a threshold is set (therefore not to make the control system is too sensitive, and does not require too much effort from the user). But since it is individually we have set, for example, the threshold as a half of the amplitude of envelope function. The results of applying the algorithm in MATLAB software environment are shown in Fig. 10.

The first chart shows the initial EMG with removed base line. The second graph - the result of the smoothing with LPF, and the third - the result of averaging. signal duration - 7 seconds, Y axis is expressed in relative units. According to the third curve, the control system will issue commands over the period of time when the threshold is exceeded.

Rewriting the signal processing algorithm for MC, it can be said that the control system (relay type) for prosthesis is ready. Then you can proceed to the implementation of the prosthetic device itself. However, attention should be paid also to the proportional control type (when the value of the user's force affects the speed and position of mechanical parts of the prosthesis).

For relay type it is sufficient to find two muscles (or muscle group), which are active enough and the user can control. Then, when straining a muscle, the prosthesis will bend any its part and when straining other - unbend. If both muscles are relaxed the prosthesis do nothing or maintain the current position. Simultaneously contracting both muscles, user can toggle between the different moving parts of the prosthesis. So constructed prosthetic management RSLSteeper and Touch Bionics. It is very effective.

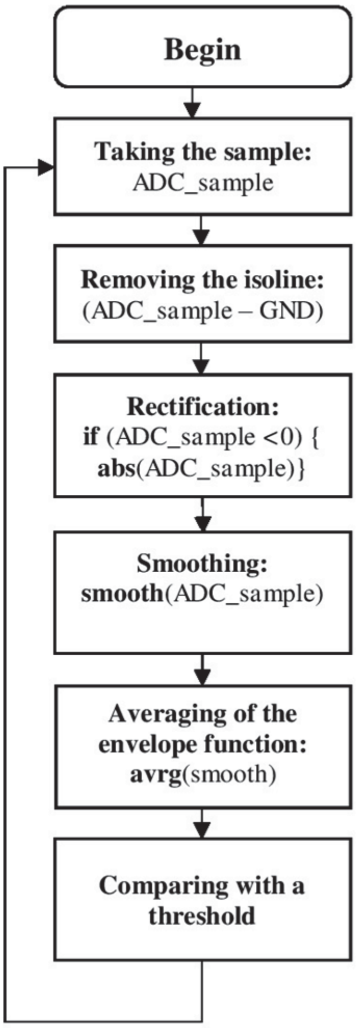

Fig. 9. Signal processing algorithm

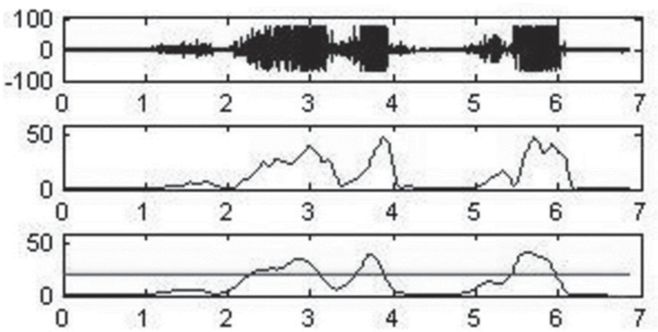

Fig. 10. The results of signal processing in MATLAB

D. Features and realization of the proportional control type

But the relay control is not the same as the natural one:

- When complete relaxing all of muscles, all moving parts of the hand taking position depending on external influences (e.g., the effect of gravity).
- When moving always take part as the agonists and antagonists muscles.

Intentionally no mention of tactile abilities of the prosthesis, the internal feedback, causes by the receptors in the hand (reflexes to muscle tension, tendon reflexes). We believe that firstly the prosthesis capable of performing the normal movements of the hand should be developed. Despite the fact that the sensitivity is very important when performing movements, if we can create a prosthesis capable of complete simulation of all the movements of the real hand, it will be possible to learn to operate the prosthesis in same way as normal hand, relying on the visual analyzer and improving motor coordination skills [11].

Before description of the proportional control, some facts should be noted:

- This control is useful when there is a simultaneous control of multiple moving parts of the prosthesis.
- For this exist a condition - remained a sufficient number of muscles or muscle groups.
- Dependence between the level of the electric voltage signal and muscle tension is non-linear [11].

Therefore, such control type will be effective for prostheses in future, when implanting electrodes into the muscles, or carrying out successfully connect to the peripheral nerves will be possible. Control system with proportional type can be considered as a modification of a relay type system. The new algorithm will look like on Fig. 11.

Prior to smoothing the signals are processed like in the relay system. Since averaging smoothes out too much rise and fall of the signal, it is replaced by another algorithm. The algorithm eliminates slight fluctuations that occurs when user try to save the position of his hand because of the constant tense of the muscles. The essence of the algorithm is as follows: to maintain the current value until the value of the envelope function will not exceed the specified range.

The first chart shows the initial EMG with removed base line. The second graph - the result of the smoothing with LPF, and the third - the result of averaging. signal duration - 7 seconds, Y axis is expressed in relative units. According to the third curve, the control system will issue commands over the period of time when the threshold is exceeded.

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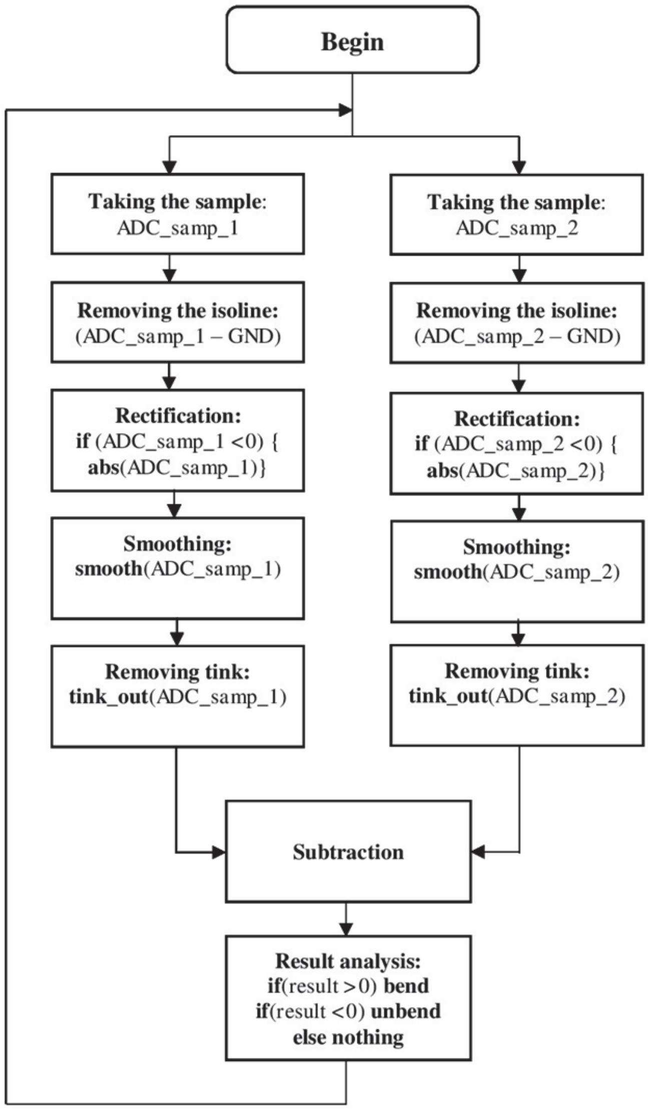

Fig. 11. The processing algorithm with a proportional control signal

When using the MATLAB language (Algorithm 1) the steps are following: the variable smooth_EMG contains values of the smoothed EMG. The output values are recorded in the *out*. The boundaries of the window are set, for example, 1.0 and 0.0. The variable *d* contains the middle value of the window. Then, algorithm begins to sort out all the input values. If the input value exceeds the upper limit, then this limit is shifted to the level of the input value. Together with it the lower bound is shifted also. Thus, the window width is not changed. The output value is the middle value of the window. It is calculated at the end and be included to an *out* array.

Algorithm 1 tink_out

```
s = size(smooth_EMG)
limitH = 1.0;
limitL = 0.0;
d = (limitH-limitL)/2;
for i=1:s(1)
   if (smooth_EMG(i) > limitH)
      limitH = smooth_EMG(i);
      limitL = limitH - d;
   else if (smooth_EMG(i) < limitL)
            limitL = smooth_EMG(i);
            limitH = limitL + d;
         end
   end
  out(i) = (limitH + limitL)/2;
end
```

But this cannot be done just like that. We do not know how these signals relate to each other. One thing is certain: if the difference is constant, the hand is held in one position. And any change indicates the presence of motion.

IV. Conclusion

Project described here will help to solve certain problems associated with the development of fully functional prostheses with control system using electromyography signal. Corresponding hardware circuits, described above, still simple and cheap enough to allow make prosthetics for extremely low price (especially with use of rapid prototyping technologies like 3D Printing). Suggested software solutions can provide reliable control of main motor functions, but due to the complexity of the implementation of electromyography control for prosthetic devices still need a lot of improvements.

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