SOME METHODS OF BIOELECTRIC SYSTEMS BUILDING FOR CONTROL BY MULTIFUNCTIONAL PROSTHESES AND PROSTHESES WITH INFORMATION FEED-BACK DEVICES

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Summary

This paper contains the examples of investigations and development of the systems for control of many functions of a prosthesis from an inherently limited number of bioelectric signals. The problems of open-loop and closed-loop bioelectric systems of control are considered.

One of the main tasks of further improvement of bioelectrically controlled prostheses is an increase of their functioning. Decision of this task is connected with a rational search for methods of building the control systems. The higher the level of amputation, the more urgent is this problem, but the more complicated is its realization.

Increase of functioning of bioelectric prostheses, when the actuating mechanisms by their independent action resemble the movements of a limb or its separate parts, as a rule demands a proportional increase in the number of controlling muscles and independent control channels. However, when such control systems are used definite difficulties arise that are connected with selection and training of several independently contracting muscles, the number of which is limited on an amputated extremity.

When the technical aspects are considered (i.e. the bulk of a system as well as some biomechanical features of motor actions, the number of which is being accomplished not simultaneously but successively in time) it is possible to draw a conclusion that application of the systems with independent control is not always advisable. For this reason both the Soviet and foreign researchers have been forced to look for possibilities of building the systems of multifunctional bioelectric prosthetic control from the limited number of command-signal sources.

Wide possibilities for an operator (a patient) to voluntarily change amplitude and time parameters of biopotentials and their derivatives allow different types of coding of controlling signals. By using proper encoders in the control system, it is possible not only to decrease the number of sources of command signals (muscles) but the number of control channels as well, but not decreasing the number of actuating mechanisms. In this case the control by a required movement is accomplished only just after switching on a proper mechanism into the control system. Selection of an actuating mechanism in such a system is performed by means of a special commutating command sent by the operator.

The principle of sequential control implies the sequence of selection and switching on the required mechanism to the main control channels depending upon stated task. To realize this it is necessary to supplement a one- or two-channel control system with a switching device whose number of stable states is equal to the number of actuating mechanisms /1, 2/.

A symmetrical trigger was applied ahead of the former logic switching devices with two stable states, that were developed at the CNIIPP and used for experimental prostheses . However, application in practice of the switching devices has shown that they have a number of disadvantages that preclude their use in prosthesis control. One of the main shortcomings is the lack of information about the position of a switching device by the operator at the moment of beginning of control by an appropriate mechanism. Consequently one of the stable states should be made more probable. In practicular, it may be used as a detector of the length of an impulse of a command signal, i.e. the switch will transit from one stable position to another due to a sequential arrival of impulses of short and long-lasting durations. If the operator has forgotten in what state the switching device is in, he sends a short impulse and after that, without any test movement, he may be sure that a quite definite actuating mechanism has been switched onto the control channels. Figure 1 is a schematic diagram of a logic switching device with two stable states for a two-channel system of control by two pairs of movements. Selection of an actuating mechanism is accomplished by sending command signals of different duration while the two controlling muscles are contracted simultaneously. In the original state a motor 1 has been switched in to the control system. Simultaneous appearance of the signals at the inputs 1 and 2 (duration of the signals being defined by selection of a time constant for the circuit (R2, R3, C2)) causes functioning of a relay

1 and switching on a motor 2. An appearance of signals of shorter duration results in returning to the original state. Such a schematic diagram may be used also with one-channel construction of a conrol system. For this purpose a logic diagram of coincidence must be changed for a detector of a speed of increment of a controlling signal /3, 4/.

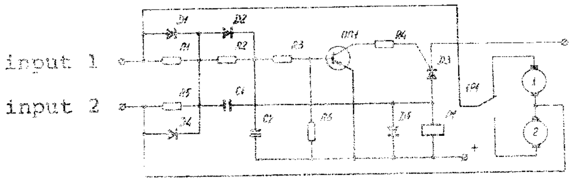

Fig. 1. A schematic diagram of a two stable state switching device.

As an example of a logic switch controlled by the autonomous channel serves a device, whose block diagram is represented in Fig. 2. With the help of such a device selective switching may be accomplished for one of the four reversible actuating mechanisms to the output of the main control channels. Transition from one stable state to another is performed sequentially by means of a short-term contraction of a muscle at two levels of tension /5/. The device includes a detector of a level and two electronic switches, of high and low level. Depending on the combination of states a commutation cell switches on the proper actuating mechanism. To prevent the changing of stable states of a trigger controlled by a small amplitude of a signal, a logic circuit for

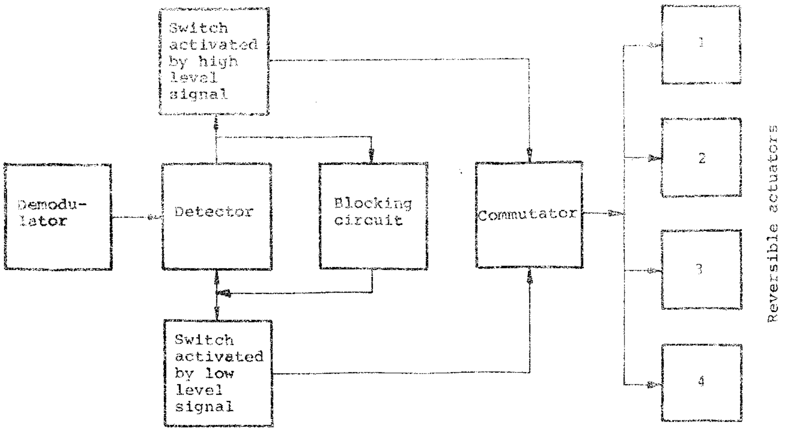

Fig. 2. A block-diagram of a one-shannel switching device to switch on one of four actuators.

blocking has been provided in the system in the process of changing the state of a trigger controlled by the larger amplitude of a signal.

An introduction of an additional switch with one unstable state to the diagram of a commutator increases significantly its functional capacities allowing use of the same control channel (one muscle) and accomplishing selective switching in twice as many the number of reversible actuating mechanisms (i.e. eight). In this case switching in one of the four actuating mechanisms, referring to the first group, is performed similarly to switching in the previous block-diagram. Nevertheless, switching in one of the four mechanisms of the second group depending of a combination of stable states of triggers, is performed by a controlling signal below the level of the first threshold.

A one-channel commutator may be considered as a device with two unstable states, i.e. for the control by a commutator a principle of an amplitude selection may be used as well. In the absence of a controlling signal the first actuating mechanism is switched in to the system, at a small level of a controlling signal - the second one, at a large level of a signal - the third one.

Use of the principle of amplitude selection of a command signal for the control by a commutator built up on a two-channel diagram allows us to carry out selective switching on of nine actuating mechanisms, depending upon the combination of the states of signals derived from two muscles /3/. Such a method of control by a commutator gives information to the operator about actuator at very moment it has been switched in to the control system.

As stated above there exist some methods of building up the systems of bioelectrical control by some actuating mechanisms from the limited number of controlling muscles. The functions of control by a commutator and an actuating mechanism in this systems are divided in time.

It is known from the prosthetic practise that the most natural and the most frequently used method of building bioelectric control systems using a pair of movements is a two-channel method where the signals derived from one or another muscle, control an actuating mechanism by the appropriate movement. However, an actuator may be reversed with one-channel diagram of a control system if an amplitude or speed selection of a command signals is used. In such a system both the functions of control by a commutator and an actuating mechanism are performed simultaneously. Figure 3 shows a block diagram of one of the versions of the system. It consists of a block of isolation of an envelope, a control channel, and a commutation channel. The control channel consists of a controlled multivibrator and a power amplifier, and the commutation channel is comprised of a speed detector, a commutator, a timer, a circuit of blocking and a circuit of delay /5/.

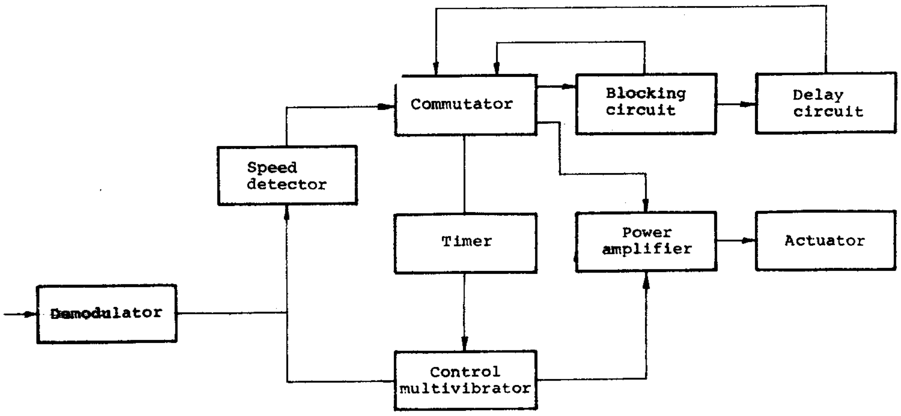

Fig. 3. A block-diagram of a one-channel control system.

The distinguishing feature of a given control system is the use of the following two parameters of a bioelectric signal: an amplitude parameter (for the control by an actuating mechanism) and a speed parameter (for the control by a commutator, changing the polarity of switching an electromotor in the circuit of a power source). The system provides proportional control of both the speed of a free displacement of an actuating mechanism and a rise time and reduction of a grasp force performed by the fingers of a prosthetic hand.

Introduction of a number of additional devices into the system is connected with specific features of this method of control. For example, a detector of speed serves for division of parameters of a controlling signal. A circuit of blocking is necessary for keeping a commutation circuit in a work state at the range of speed changing of the movement of an actuator. A timer of a multivibrator is introduced to prevent involuntary movement of an actuator when a control signal is introduced by a commutating cell. An introduction of the circuit of time dely of a commutating circuit in a work state is explained by the presence of a time constant of the operator reaction before the beginning of control by an opposite movement of an actuator.

It should be noted here that acceptable functioning of a prosthesis depends on more then the number of active movements it provides. First of all, prosthetic functioning depends on a quality of performance by a patient , and his energy consumption, which in its turn is determined by the level of amputation and the number of limbs lost.

When considering separately each actuating mechanism, for example, of an above-elbow prosthesis (it may be a hand, rotation mechanism, elbow unit etc.), we may see that all these mechanism must have different characteristics, both of force and speed.

Therefore the system of multifunctional bioelectric control of the prosthesis from the limited number of muscles must provide the possibility of a change of parameters of a conversion unit according to the parameters of an actuating mechanism being switched in.

Selection of a method of control for an actuating mechanism (threshold or proportional one) has no less meaning in regard to the energy consumption by the patient. Investigations carried out at the Central Research Institute for Prosthesis in Moscow have shown the advisability of use of a threshold system for the control by the movements of fingers in a prosthetic hand. A force grasp is adjusted by means of a time parameter /6/. As far as control of an elbow mechanism is concerned it is the most advisable to apply combined threshold- proportional control system which allows, depending on a character of a function performed, the choice of the most convenient operating conditions for the patient. Selection of the operating conditions depends upon the speed of transmission of the control signal.

In the last few years various investigators have been developing proportional bioelectric control systems in an attempt to increase significantly the function of prostheses. Most of the investigators prefer a method of conversion of a bioelectric signal into a sequence of the square-wave impulses, influencing directly the electric drives of actuating mechanisms. Characteristics of these control systems may be improved greatly when a feed back is introduced.

Figure 4 shows a schematic diagram of a pulsed device for a threshold system of a control by finger movements in a prosthetic hand with adjustable force of the grasp by means of a time parameter (a schematic diagram of a system developed at the CNIIPP).

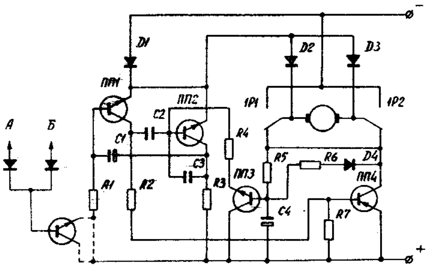

Fig. 4. A schematic siagram of a threshold - proportional control system.

The device consists of a multivibrator (PP1 - PP3 type transistors); a power amplifier (PP4 type transistor); an integrator, changing parameters of the multivibrator (a diode D4, a resistor R6, a capacitor C4); a circuit of blocking (a resistor R5). The device works in the following manner: when a signal is absent at the inputs of the control system, the contacts of the output relays R1 and R2 are normally shorted out. In this position the circuit is deenergized. The appearance of a control signal of a threshold magnitude at the input of the channel 1 causes operation of the relay R1 whose moving contact is set on the minus contact of a power source. This causes switching of an electromotor of a hand drive into the collector circuit of a PP4 type transistor and simultaneous triggering of a multivibrator. As a result square-wave impulses arrive onto the motor.

It is selected such a duration of impulses of the multivibrator in order to provide minimum starting moment of the motor. Nevertheless, the frequency of impulses must be maximum in order to provide maximum possible speed of a free displacement of the fingers.

When the fingers touch an object a current rises in the circuit of the motor. Simultaneously a negative potential (on the collector of a PP4 transistor) rises, which, in its turn, arrives at the integrator. A voltage on the integrator in dependence of the duration of action of controlling signal, changes shifting on the base of PP3 transistor switched into the discharging circuit of a capacitor C2, what causes the change of duration of impulses and respectively the change of a grasp force. Cessation of supply of a controlling signal results in blocking of a capacitor C4 and transition of the device into initial state. Reverse of the electric motor is performed by a controlling signal to the input of a channel 2.

The device may be used also in the systems of a proportional control by actuating mechanisms of a prosthesis. In this case, a transistor must be switched in series with resistor R1 into a charging-discharging circuit of a capacitor C1. The points A and B (on a schematic diagram) must be connected with outputs of integrating blocks of appropriate control channels. With an increase in the number and quality of controlled prosthetic functions it becomes even more necessary to introduce not only automatic feedback devices but sensory feedback devices as well. Such a necessity results both from basic theories about the meaning of feedback in the control and coordination of movements, and from the features of a bioelectric control.

The application of feedback devices gives the patient possibility to transfer information not only about the parameters of a controlled object (a grasp force with hand fingers, position and speed of the articulation displacements, a force moment), but about the characteristics of the objects it is handling (weight of the object, quality of the surface, form of the objects, etc.).

To transfer information about the parameters of the actuating mechanism, we used vibrational frequency-pulsed irritations. According to physiological and technical data the available frequency range was from 1 to 50 cps. This is explained by amplitude-frequency characteristics of receptors, perceiving vibrational irritations, by a mechanical impedance of the skin and selection of a definite duration of impulses which depends on mechanical constants of electromegnetic vibrator /7/.

Investigations of differential thresholds have shown that the subjects discriminate up to 30 differential steps in this frequency range. Such precision of perception of feedback signals allows us to suppose that the subject can evaluate the changes of a grasp force magnitude up to 150-200 gs.

A comparison of characteristics of a feedback channel signal and a control channel signal should be made for an optimum design of a closed-loop bioelectric control systems. Therefore an investigation of an operator's possibilities only to perception and processing of feedback signals does not permit confirmation of the fact that introduction of these signals will increase the precision of control. The precision of dosage of control signals may be turned out higher than the precision of perception of feedback signals.

By using information it is possible to compare characteristics of a feedback channel and a control channel. The information capacity of these channels has been investigated, i.e. the definite number of apsolutely distinguishable levels, which may be counted in the controlling signals, transferred by a man, or may be perceived by a man through a feedback channel.

Experiments which had to reveal absolutely distinguishable levels in the control signal have shown that at the presence of even three levels the curves of distribution of biopotential amplitude are crossed with each other. So even three levels are distinguished not precisely and the volume of information transferred does not exceed 1.6 bit /8/.

In an analogous way a sensorimotor channel has been investigated. From 3 to 8 alternating frequencies (at the range of 1 - 50 cps) have been represented to the operator at a random succession at equal logarithmic intervals. The experiments have shown, that the operator distinguishes up to 7 alternating frequencies (the volume of an input information 2.8 bit) /9/.

A forearm prosthesis developed at the CNIIPP (Fig. 5) provides bioelectric control by the fingers of an artificial hand and a feedback channel /10, 11/ which transfers information to the patient on the value of the force of grasp on an object. The prosthesis consists of the following main units: a two-channel electronic unit of control 1-6; a hand with a pressure transducer 7, 8; an electronic feedback unit 9-12; an electromagnetic vibrator 13 and a power source 14. Bioelectric signals obtained by means of surface electrodes, are amplified and pass to a block for detection, smoothing and further amplification. The signals then pass to the voltage-to-pulse frequency converter. Pulse frequency of the converter is proportional to the amplitude of controlling signals. From the output of the converter impulses arrive to the power amplifier, at the load of which an electromotor has been switched in. Approprite relays accomplish commutation of a rotation direction of an electromotor armature.

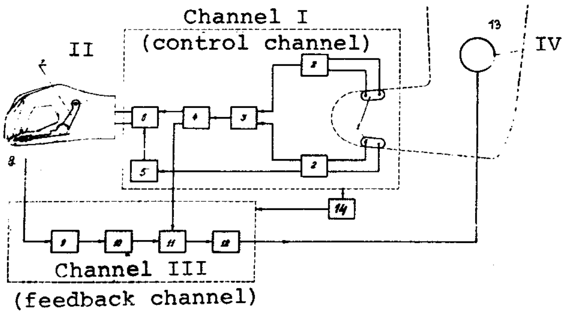

Fig. 5. A block-diagram of a bioelectric prosthesis with a feedback.

Feedback signals are perceived by the pressure transducer, placed in the 1st finger of the hand. Then signals pass to the amplifier. The output signal from the amplifier arrives to the block of conversion of the signal to square-wave impulses, frequency-modulated. A transmission factor of a feedback channel is 120-130 g/cps. With the help of a power amplifier these impulses control the vibrator. There is a special block in the feedback device limiting time of action of vibrational irritations perceived by the patient. The block is triggered by the signals picked-up from the power amplifier and switches on the feedback channel for 2-3 secs. After that automatic switching off of the feedback channel takes place. Therefore vibrational impulses arise only when regulation of the grasp of the object is made by the fingers.

Research of functional features of a control system by a bioelectric prosthesis with vibrational feedback has been carried out with the help of a mode of compensating tracking. Transient characteristics of regulation of a grasp force by the prosthetic fingers have been obtained. Dynamic characteristics and static disadvantages of regulation have been evaluated.

As follows from the comparison of the data obtained, selected parameters of vibrational feedback connection (gear ratio of the channel, frequency, amplitude, form of a signal) allow the operator to evaluate the force of the grasp exerted by the fingers of the artificial hand, with precision approximating the appropriate indexes of regulation of a grasp force by the fingers of a healthy hand (Fig. 6). However the time required for regulation of a grasp force of a prosthetic hand by a patient is twice that for a healthy hand.

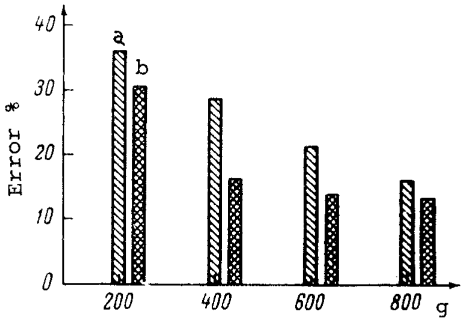

Fig. 6. Precision of a grasp force
a) artificial prosthetic fingers with a feedback device;
b) fingers of a healthy hand.

Some quantity of the prostheses with the feedback device has been manufactured. An experimantal prosthetic fitting has been carried out for ten patient. The results of experiments are being processed.

At present designing of feedback devices for the prostheses with the controlled functions becomes urgent (for example, for transfer of the grasp attempt and displacement of fingers of an artificial hand). We have studied different methods of coding of the information transferred: stimuli acting in parallel and having the same alphabet; an ordinary stimulus carrying information on two parameters of the object; a localized stimulus (phantom) with simultaneous change of acting stimuli frequency /12/. A comparison of an information capacity of above-mentioned methods of coding (Fig. 7) has permitted the choice of the best one-displacement of a phantom with simultaneous change of the frequency of stimuli. The experiments have shown that the location of a stimulus perceived subjectively isconnected by functions with correlation of stimuli intensities. In this case the location of a phantom is not changed practically as the frequency is varied /12/.

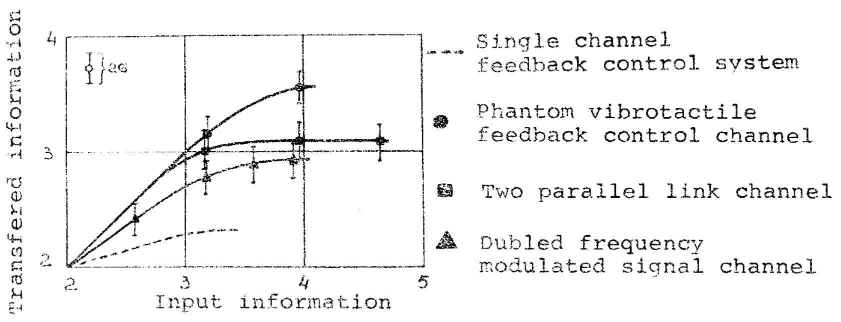

Fig. 7. Information capacity of different vibrotactile channels.

The mode of compensating tracking has confirmed the possibility of discrete tracking out pulsed frequency and the location of a phantom.

The experiments carried out have permitted us to begin working out the feedback devices to transfer the information to the patient both of the displacement and of the force parameters at separate articulations of the prosthesis.

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