Proc. of 5th Int. Symp. on External Control of Human Extremities, ETAN, Yugoslavia, Dubrovnik 1975.

AN ABOVE ELBOW ARM PROSTHESIS

M. Rakić

Abstract

The problem of semiautomatic control of an externally powered above-albow arm prosthesis with four degrees of freedom is treated in the paper. A new control concept is presented based on the following. The volitional signals are assumed to be generated by the patient stump movement. These signals are functionally interrelated by processing in a small portable computer. The computer generates control signals to be applied to the servomechanisms for actuation of the prosthesis.

In order to evaluate the control concept, a pilot above-elbow prosthetic system has been developed. The description of the arm prosthetic system are presented in the paper in details.

Introduction

A patient will not be able to control a multifunctional upper-extremity prosthesis unless it is conceived as a complex control system and carefully designed to fulfill specific requirements. This is a result of the complexity of the actual prosthesis as well as the inability of the patient to genrate a sufficient number of simultaneous volitional signals necessary for controlling the prosthesis. The purpose of the control system is not only to enable the patient to control the prosthesis but also to make this task as easy as possible. Generally, this can be accomplished if the control system:

(a) Reduces the number of volitional signals which the patient must generate to control the prosthesis in such a way that, regarding its rehabilitory capacity, there is no essential loss in the controllability of the system within the natural bounds of motion of the arm.

(b) Enables a sufficiently simple method of generating volitional signals and a sufficiently simple relationship between the state of the prosthesis and these signals, providing that this relationship should, to the greatest possible degree, correspound to the natural perception of space and control of complex arm mouvements.

(c) Enables adaptivity of the system or at least a reduction of its sensitivity to dominant external disturbance.

In order for a control system to have these capabilities a corresponding signal transformation is required, particularly, a transformation of volitional input signals into control signals. Apparently, the extent and the compexity of the transformation depends upon the strictness of the desired specifications. It is particularly evident that the need to reduce the controllability of the system and the complexity of the signal transformation will be lesser if the number of volitional signals is greater.

On the other hand, due to practical reasons, the necessary signal transformation must not be too complicated nor too extensive since that would require a process computer with an appropriate capacity which is not compatible with the objective and the way of use of an upper-extremity prosthesis.

On the basis of these conclusions, in order to obtain a compromising solution, the development of the multifunctional above-elbow arm prosthesis system proceeded under the following assumptions:

- By careful selection of the location and the method for generating volitional signal and using simple relationship between the state of the prosthesis and these signals the patient should be able to easily realize and make efficient use of a large number of continuous and discrete signals.
- The controllability of the system should be retained to a level which is relevant considerring the rehabilitory capacity of the prosthesis.
- The transformation of volitional into control signals should be as simple as possible, even if this means that precise control of the prosthesis along the most suitable trajectories must be discarded if necessary.
- The sensitivity of the system to the most dominant external

Class of Patients for which the Prosthesis is Intended

The prosthesis is intended for patients with above-elbow amputations. The amputations can be either unilateral or bilateral. It is assumed that the amputation of the arm is such that the free length from the end of the stump to the artificial albow is at least 10 cm long. Finally, it is assumed that the patient can perform the following movements with the stump: elevation - depression, extension - flexion and medial - lateral rotation, even if only for very small angles.

Hardware Concept for the Prosthesis

The hardware part of the prosthesis is of a modular type. These modules are: the supporting part wich carries the prosthesis, the above-elbow part, the elbow, the forearm and the hand prosthesis. These modules could be independently interchanged.

The prosthesis rest on the shoulder, on the corresponding side of the body. The supporting part is constructed so that the actual shoulder joint is as free as possible, in order to enable the patient to execute unrestricted stump movements.

The prosthesis has the following active movements (the notation and the total angle of the movement are given):

β_1	- rotation of the above-elbow part	(180^o)
β_2	- elbow flexion - extension	(135^o)
β_3	- supination - pronation	(135^o)
β_{30}	- wrist flexion - extension	(60^o)
β_4	- prehension	

Complet controllability of the system within the natural bounds of motion of the arm would require two independent active movements of the wrist joint and a greater number of degrees of freedom of the hand prosthesis. However, this would make the control problem very difficult. In order to simplify the control problem, the controllability of the system is somewhat reduced because wrist flexion is mechanically and therefore, functionally linked with supination - pronation or, formally,

$$\beta_{30} = \beta\lambda_3$$

where λ is an adjustable parameter. Hence, wrist flexion is not an independent degree of freedom so that the static state of the prosthesis is determined by

$$\bar{\beta} = [\beta_1 \ \beta_2 \ \beta_3 \ \beta_4]^T$$

In order to realize the movements mentioned above, four servo-motors are installed in the arm prosthesis.

Lower Level of the Control System

One of the requirments mentioned is the reduction of the system sensitivity to the most dominant external distrubances. Taking into account that the basic control objective is to bring the prosthesis into a desired state, the most important external disturbances of the static and dynamic performance of the system are:

- the influence of the gravitational forces on the prosthesis as well as on the objects which are carried by the prosthesis,
- the influence of other external forces and torques which the prosthesis must overcome while performing the desired activities.

In order to reduce the sensitivity of the system to these disturbances, the active movements, that is control of the appropriate servo-motors is realized by way of servomechanisms. This system, consisting of four servomechanisms, is the lower level of the control system.

Since the servomechanisms are stable and with a sufficiently fast response considreing the required speed of movement then the influence of the internal inertial and other opposing forces and torques, i.e. the dynamics of the actual system, can be neglected with little loss of accuracy. Therefore, the lower control level can be represented statically with sufficient precusion by the algebraic relation:

$$\bar{\beta} = K \ \bar{u}$$

where

$$\bar{u} = [u_1 \ u_2 \ u_3 \ u_4]^T$$

is the control signal vector which acts at the input of the servomechanisms, and

$$K = \begin{bmatrix} K_1 & 0 & 0 & 0 \\ 0 & K_2 & 0 & 0 \\ 0 & 0 & K_3 & 0 \\ 0 & 0 & 0 & K_4 \end{bmatrix}$$

is the gain-factor matrix. The constants K_k, $(k=1,2,3,4)$ are determined from:

$$K_k = \frac{\beta_{k\ max}}{u_{max}} , \ (k = 1,2,3,4)$$

where: $\beta_{k\ max}$, $(k = 1,2,3,4)$ is the total angle of the active movements and u_{max} is the maximal value of the components of the control signal vector $\bar{u}$.

Generation of Volitional Signals

In order to control the prosthesis the patient has to realize a set of volitional signals which are suitably transformed into components of the control signal vector $\bar{u}$. Special care was taken with this problem since it is one of the most delicate problems which concerns the solution of upper-extremity multifunctional prosthesis. By suitable choice of locations and the method of generating these signals it was attempted to enable the patient to relatively easily realize a larger number of simultaneous signals. The movements which the patient can realize with his stump and shoulder proved as an extremely efficient method for genereting these signals. In accord with the general solution of the control system is was decided that the patient should realize four continuous and one discrete signal.

For controling the arm prosthesis, exepting the hand prosthesis, three continuous signals are used which the patient generates by

α_1 - small medial - lateral rotation of the stump
α_2 - elevation - depression of the stump
α_3 - extension - flexion of the stump

These signals are obtained from transducers (potentiometers) built into the supporting part of the prosthesis. Hence, by moving the stump, the patient performs elevation - depression and extension - flexion of the complete prosthesis, and concurrently generates volitional signals for all active movements of the prosthesis exept for prehension. The stump movements with which

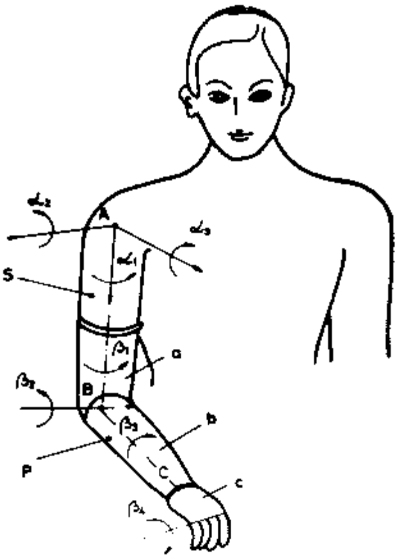

Fig. 1.

S - stump
A - shoulder joint
B - elbow joint
C - wrist joint

P - above-elbow arm prosthesis
a - above-elbow part of the prosthesis
b - forearm of the prosthesis
c - hand prosthesis

the volitional signals α_k, $(k = 1,2,3)$ are realized, the active movements of the prosthesis β_k, $(k = 1,2,3)$ and the adopted positive directions of the movements are shown in Fig. 1.

In order to control the hand prostnesis, the patient has to generate an additional volitional control signal (α_4) in the region of the shoulder. The method of generating this signal depends on the type of the hand prosthesis used and will be described in detail in a special section.

For the control philosophy adopted a discrete signal with two states is also necessary

$$\alpha_o = \{0, 1\}$$

The patient realize this signal by a movement of the shoulder activating a contact-switch which is built into the supporting part of the prostesis.

Expepting this discrete signal, the set of volitional signals can be written as an input signal vector:

$$\bar{\alpha} = [\alpha_1 \ \alpha_2 \ \alpha_3 \ \alpha_4]^T$$

Higher level of the Control System

The task of the higher level of the control system is to transform the input signal vector $\bar{\alpha}$ in a suitable way into the control signal vector $\bar{u}$, which acts upon the inputs of the servomechanisms. Generally, this rapid electronic processing of input signals into control signals, can be represented as

$$\bar{u} = F(\bar{\alpha})$$

Since the action of the lower level of the control system, that is the servomechanisms, is described by

$$\bar{\beta} = K \ \bar{u}$$

it directly results that the complete control system can be described staticlly by

$$\bar{\beta} = KF(\bar{\alpha})$$

and can by represented by the block diagram in Fig. 2.

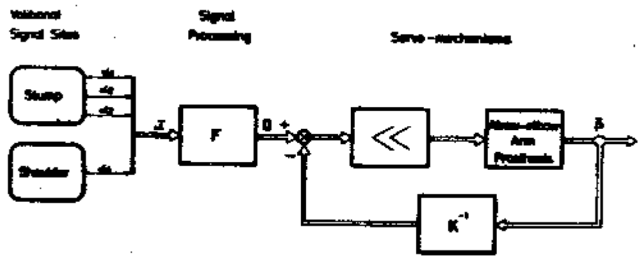

Fig. 2.

Let us consider the stump and the prosthesis as a unique composed system. On the basis of all that has been said, the static state of these system would be defined by the vector

$$\bar{y} = [\alpha_2 \; \alpha_3 \; \beta_1 \; \beta_2 \; \beta_3 \; \beta_4]^T$$

Because of the dependence of the prosthesis state vector $\bar{\beta}$ on the input signal vector $\bar{\alpha}$, it comes out that a unique functional relation existes:

$$\bar{y} = \psi(\bar{\alpha})$$

Bearing in mind that the volitional signal α_4, which is the only one not genereted by a stump movement, is intended solely for controling the hand prosthesis, it can be easily concluded that the position and movement of the whole composed stump-prosthesis system, particularly the position and orientation of the hand prosthesis in space and its motion, will be uniquely defined by the position and motion of the stump. This fact should enable the patient easy control of the prosthesis.

Conversely, a consistent preordanied functional relationship between the input signal vector $\bar{\alpha}$ and the prosthesis state vector $\bar{\beta}$ represents a contraint upon the controllability of the system, as a consequence of the physical connection between the prosthesis and the stump. This can be formally concluded also from the fact that the state vector of the composed system $\bar{y}$ is six-dimensional whereas the input signal vector $\bar{\alpha}$ is four-dimensional.

In order to eleminate these shortcomings and to enable the patient to have sufficient conscious control in selecting the trajectory along which he is guiding the prosthesis to the desired position, as well as controlling the desired hand orientation in space, tree different transformation of the input signal vector $\bar{\alpha}$ into the state vector of the prosthesis $\bar{\beta}$ were adopted. The patient has the posibility to select, at any moment, the mode of input signal transformation. This is accomplished with the discret signal α_o. This signal is transformed by a cyclic shift-register into another discrete signal u_o with three possible states:

$$u_o = \{1, 2, 3\}$$

The signal u_o acts upon an electronic switching system so that the signal transformation mode is determined by the state of the signal u_o. According to this, the final concept of the prosthesis control system could be represented by the block diagram in Fig. 3.

During the execution of a movement, by successively selecting the signal transformation mode the patient could guide the prosthesis approximately along the desired trajectory to the desired final position, keeping at the same time, a desired orientation of the hand in space.

It can now be seen that the advantage of the adopted control concept lies in the fact that the patient can control the whole prosthesis, exept for the hand prosthesis merely by moving the stump and using a single additional discrete signal obtained by engaging a contact-switch. Movements of individual parts of the prosthesis are automatically synchronized. It is reasonable to assume that, in time (i.e. with training), the patient would accept on his synergic level, the functional relationship between stump and prosthesis motions, providing that this relationship is simple enough.

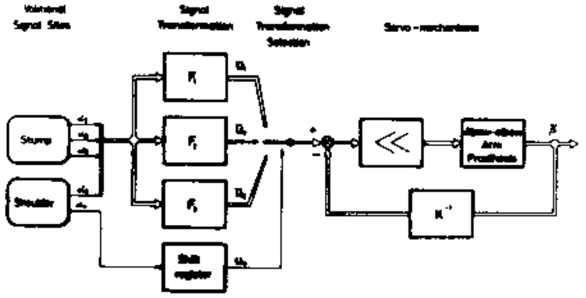

Fig. 3.

Signal Processin

In order to select suitable transformation of the input signal vector $\bar{\alpha}$ into the control signal vector $\bar{u}$ extensive experimental reserch was performed. This experimentation was performed using an anthropomorphic manipulator and a Varian 620/i digital computer. On the basis of the results of the experiments the simplest types of linear signal transformations were finally adopted:

$$\bar{u} = F_i(\bar{\alpha}) = A_i\bar{\alpha} + B_i, \quad (i = 1,2,3)$$

that is,

$$\bar{\beta} = KF_i(\bar{\alpha}) = KA_i\bar{\alpha} + KB_i, \quad (i = 1,2,3)$$

since this resulted in the simplest relationship between the prosthesis state vector and the volitional input signals, which is, due to the reasons explanied earilier, one of the basic requirements for easy control of the prosthesis.

For the same reason, the following matrices KA_i, $(i = 1,2,3)$ and KB_i, $(i = 1,2,3)$ were chosen for the individual signal transformations:

$$KA_1 = \begin{bmatrix} c_1 & 0 & 0 & 0 \\ 0 & c_2 & 0 & 0 \\ 0 & 0 & c_3 & 0 \\ 0 & 0 & 0 & c_4 \end{bmatrix} \qquad KB_1 = \begin{bmatrix} \beta_1(t_j) - c_1\alpha_1(t_j) \\ \beta_2(t_j) - c_2\alpha_2(t_j) \\ \beta_3(t_j) - c_3\alpha_3(t_j) \\ 0 \end{bmatrix}$$

$$KA_2 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & c_4 \end{bmatrix} \qquad KB_2 = \begin{bmatrix} \beta_1(t_j) \\ \beta_2(t_j) \\ \beta_3(t_j) \\ 0 \end{bmatrix}$$

$$KA_3 = \begin{bmatrix} c_1 & 0 & 0 & 0 \\ 0 & -c_2 & 0 & 0 \\ 0 & 0 & c_3 & 0 \\ 0 & 0 & 0 & c_4 \end{bmatrix} \qquad KB_3 = \begin{bmatrix} \beta_1(t_j) - c_1\alpha_1(t_j) \\ \beta_2(t_j) - c_2\alpha_2(t_j) \\ \beta_3(t_j) - c_3\alpha_3(t_j) \\ 0 \end{bmatrix}$$

were t_j, $(j = 1,2,\ldots)$ designates the moments prior to switshing between signal transformation modes, and $\alpha_k(t_j)$, $(k = 1,2,3)$ and $\beta_k(t_j)$, $(k = 1,2,3)$, the corresponding input signals and angles of the prostesis at that moment respectively. Evidently, the matrices KB_i, $(i = 1,2,3)$ are introduced to ensure that the prosthesis will not change its position at the moment of switching from one signal transformation mode to another.

A brief analysis of the matrices KA_i, $(i = 1,2,3)$ reveals that the signal transformations adopted yield a very simple relationship between stump and prosthesis movements.

In case of signal transformation mode (1) the following relationships exist:

- a small medial - lateral rotation of the stump (α_1) causes a proportionally amplified rotation of the above-elbow part of the prosthesis (β_1);
- elevation of the stump (α_2) causes elbow flexion (β_2) and depression - elbow extension;
- extension - flexion of the stump (α_3) causes simultaneous supination - pronation of the forearm (β_3) and wrist flexion (β_{30});
- the patient controls the hand prosthesis (i.e. prehension β_4), as alredy mentioned with a separate signal (α_4) generated in the region of the corresponding shoulder.

For signal transformation mode (3), the same relationships exist between stump and prosthesis movements, except that elevation of the stump (α_2) causes elbow extension ($-\beta_2$) whereas a motion in opposite direction results in elbow flexion.

Finally, for signal transformation mode (2) stump motion does not activate the prosthesis. Therefore, this mode enables the patient to change the position of the prosthesis, without changing the angles β_k, $(k = 1,2,3)$. However, the patient can still control the hand prosthesis.

Some Experimental Results

Experiments performed with the control system described indicated that it is possible to chouse such values for the constants c_k, $(k = 1,2,3,4)$ that it becomes relatively simple to control the prosthesis, that is, to bring the hand prosthesis into the desired position in space, moving it approximately along a desired trajectory, controlling at the same time the orientation of the hand prosthesis in space.

If only terminal orientation of the hand prosthesis was required, a single movement lastest not longer than 5 seconds, with a maximum of two changes in signal transformation modes at appropriately selected moments. Hawever, if continuous hand orientation was required along the whole manipulator trajectory, execution of movements was slower, due to the greater number of signal transformation mode changes and the greater concentration necessery for performing the movement. The duration of th vement and the number of signal transformation mode changes to a great extend on the initial and the desired final state of the prosthesis.

Since the appropriate values of the constants c_k ($k = 1,2,3$) depend on the mobility of the stump, the system is realized so that it is possible to adjust these constants within a wide interval of values. As a result the prosthesis can be adapted to individual patients, according to their capabilities and requirements.

The Hand Prosthesis

Since the prosthesis is of the modular type, there is no difficulty (exept for minimal adaptations) in connecting any of the existing externally powered hand prosthesis on the market. Accordingly, reserch was performed with two different hand prosthesis: the Belgrade hand prosthesis and the Otto Bock myo-electric hand prosthesis. These two types were selected because, from the aspect of control, they belong to different groups. The Belgrade Hand prosthesis is a multifunctional hand prosthesis which is controlled by a signal from a transducer of the potentiometer type, while the Otto Bock hand prosthesis has myo-electric control.

When the Belgrade hand prosthesis was used, the volitional signal for controlling it (α_4) was obtained from the potentiometric transducer which was on one side connected to the supporting part of the prosthesis, and the other to a belt tied about the waist. The patient acts upon the potentiometer by a slight shrugging of the shoulder.

In case of the Otto Bock prosthesis, the myo-electric signal (α_4) can be obtained from electrodes set obove the pectoralis major - pars abdominalis muscle.

The Hardware of the Prosthesis System

(a) Supporting part

The support which servs to carry the prosthesis and, of the same time, enables the generation of volitional signals is shown in Fig. 4. This unit consists of:

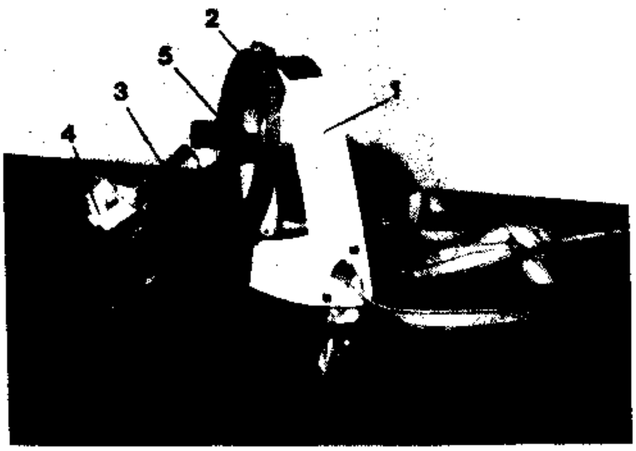

Fig. 4.

- the basic support with suspenders (1),
- a revolving ring with a buil-in potentiometer for generating volitional signal α_2(2),
- support levers (3) with a potentiometer (5) for generating volitional signal α_3,
- two concentric revolvable rings with a built-in potentiometer for generation volitional signal α_1(4).

(b) Above-elbow arm prosthesis

The above-elbow arm prosthesis is shown in Fig. 5. It is of a modular type. The modules are.

- supporting part (1)
- above-elbow part (2)
- elbow (3)
- forearm (4)
- hand prosthesis (5)

This experimental model of the prosthesis is covered hy a plastic sporgy covering which is not shown in Fig. 5. since it has been removed. The total weight of the prosthesis is 2.9 kg.

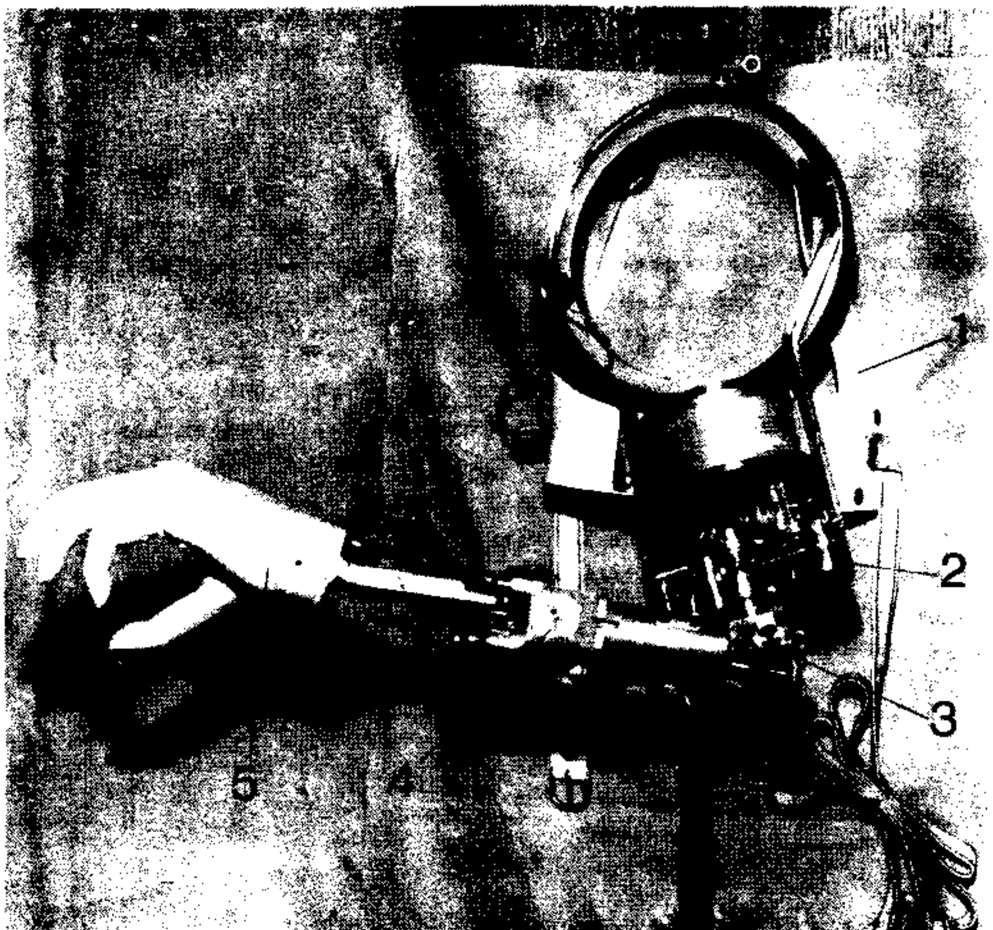

Fig. 5.

(c) Electronics

The electronic part of the prosthesis control system consists of a input signals processor, four servoamplifiers and a voltage stabilizer. The compelte electronic system is 12 cm x 14 cm x 18 cm and together with the box weights 1.4 kg.

As a power supply for the prosthesis control system a D.C. voltage of 24 V is required. During the execution of movements the average power consumation is approximately 24 W. As a voltage source dry-cell batteries are used.

Associates and Financial Support

Development of the prosthesis and the research were performed a the Mihailo Pupin Institute in Belgrade. The project was financed by the Social and Rehabilitation Service, Washington, D.C., U.S.A.

During research on the project I have often had dicussions with Dr Momčilo Gavrilović. His suggestions during these exchanges were very helpful. Dr Zoran Stojiljković devloped the electronics for the control system, and all computer programs for the experimental research were done by Katarina Dujmović, B.Sc. The hardware part of the prosthesis was realized with the help of technicians Živojin Stojanović and Danilo Popović. I am grateful to all of them for their assistance.

(c) Electronics

The electronic part of the prosthesis control system consists of a input signals processor, four servoamplifiers and a voltage stabilizer. The compelte electronic system is 12 cm x 14 cm x 18 cm and together with the box weights 1.4 kg.

As a power supply for the prosthesis control system a D.C. voltage of 24 V is required. During the execution of movements the average power consumation is approximately 24 W. As a voltage source dry-cell batteries are used.

Associates and Financial Support

Development of the prosthesis and the research were performed a the Mihailo Pupin Institute in Belgrade. The project was financed by the Social and Rehabilitation Service, Washington, D.C., U.S.A.

During research on the project I have often had dicussions with Dr Momčilo Gavrilović. His suggestions during these exchanges were very helpful. Dr Zoran Stojiljković devloped the electronics for the control system, and all computer programs for the experimental research were done by Katarina Dujmović, B.Sc. The hardware part of the prosthesis was realized with the help of technicians Živojin Stojanović and Danilo Popović. I am grateful to all of them for their assistance.