THE MECHANISM OF THE PROSTHESIS FOR UPPER HUMAN LIMB – MAIN ASPECTS REGARDING: SINTHESIS, ANALYSIS, DESIGN AND FUNCTIONAL SIMULATION

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This paper describes the main stages of structural and cinematic synthesis and analysis, design and functional simulation regarding the mechanism of the human hand prosthesis. For the structural scheme, one uses three pivot joints only, and one movement for closing the palm. The technical project is complete. One command scheme is shown too. The functional simulation has been made to identify the best solutions to optimize the constructive solution and to use the prosthesis by human operator.

1. INTRODUCTION

Human upper limbs are the most complex and at the same time the most useful kinematical part of the human body and, as a result, there were and there have been various attempts to reduce their possible disability degrees.

There are three main solutions in this case, whose purpose is to reduce or to eliminate different disability degrees, if the upper human limb is lost: by transplanting it, using internal prostheses or just prostheses.

There are three main types of prostheses for the human hand (palm): *cosmetic prostheses, prosthetic tools and functional prostheses.*

Of these types of prostheses, *cosmetic prostheses* are commonly used, mainly due to their low cost. The name refers to the fact that they are not functional, and they are used only to replace in a rigid manner, the missing part, in our case, the palm.

Fixed fingers mean that they cannot be modelled in another position than the existing one, by default. The mobile ones, thanks to the materials they are made of, allow modelling in a certain position of the fingers, and they remain in this position until the next remodelling. The prosthesis must be made taking into account the size of the opposite existing hand. Since it is an aesthetic prosthesis, these basic features are important: the colour of the outer material – of the skin, the details of the hand, the shape of the fingers and nails, etc., briefly, *the naturalness* of the hand.

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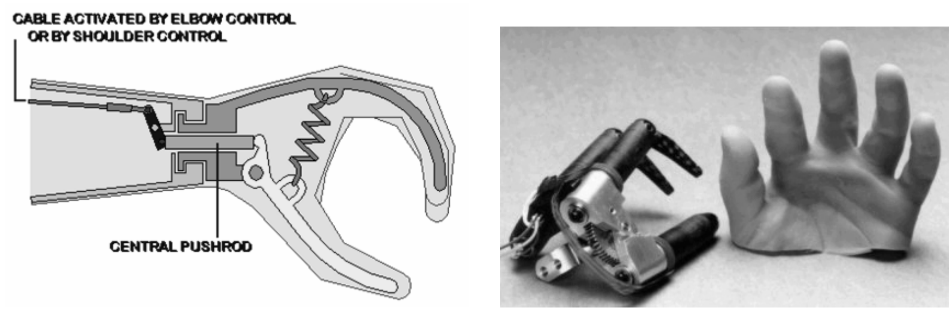
In addition to cosmetic prostheses, which focus on the outside to be as aesthetic as possible, and do not consider their functional and useful part, there are *prosthetic tools*. In their case, the primary objective is their work usefulness. Focusing on this, the fingers may be replaced by some "hooks" that can be much better for work than any artificial fingers. These "hooks" can grab smaller objects. They are almost non-aesthetic and may vary depending on utility. Even the material of the prosthesis can vary depending on situation and needs. Prosthetic tools based on a mechanism (a simple one) must be operated. This is achieved either by movements of the rest of the arm or by special miniature electric motors, or there is the possibility to operate using artificial muscles. They are commanded mechanically, electrically (via buttons or bio signals), electronically, or by voice.

If we want prosthesis aesthetically designed, as well as useful, we choose the so-called *functional prostheses*. They emphasize both the aesthetics, being similar to the hand, but they also have a degree of functionality, based, of course, on a mechanism. There are many variants of prostheses, from the simplest to very complex structures. In terms of the constructive elements used, they are articulated bar mechanisms, gear wheeled ones, with wires and wheels, etc. Concerning the phalanges drive, starting from the hand bio mechanism, four main solutions are especially used. They are mechanisms with wires, for the fingers’ extension, in parallel with springs for extension, gripping mechanism with wires, in parallel with extension springs, wired mechanism for extension and gripping, and mechanism with articulated bars for both movements of the phalanges. As far as the prosthesis’ degree of functionality is concerned, it derives from the degree of mobility provided by the construction of the mechanism that drives the phalanges.

An example of functional prosthesis is in Fig. 1.1, a normally closed prosthesis [7]. It is driven by a cable from the elbow joint or the shoulder one. The cable, connected to a lever, drives the central pushing rod, which will open the prosthesis. The recovery is accomplished by the action of a spring. Thus, mobility is achieved only by the thumb, the other four fingers being fixed. Phalanges drive can be done by gear as well, like in the figure below (Fig. 1.1 b) [7].



a b

Fig. 1.1 – Functional prostheses.

At this prosthesis, both the thumb and the other fingers are mobile. Alongside there is a glove like human skin that covers the prosthesis, giving it, aesthetically, an appearance as real as possible.

For the forearm, elbow and arm prostheses there are cosmetic prostheses, but usually minimum functionality must be provided so that all the other solutions fall into the category of functional prostheses.

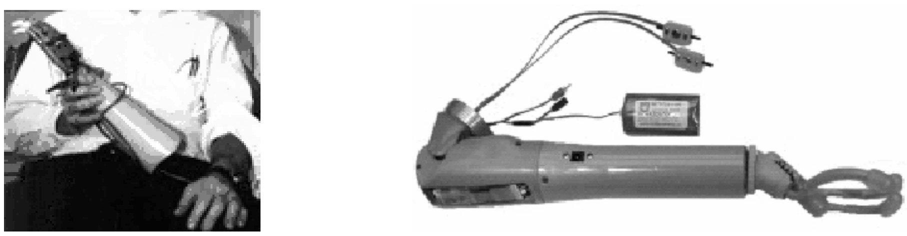
In the case of prostheses for hand and forearm, in general there is prosthesis for the hand itself with a small extension, depending on the size of the blunt area. This extension is actually a cosmetic prosthesis for the forearm, which fixes the upper limb prosthesis for the hand or includes some elements for their command and / or drive. However there are variants in which besides the joints of the hand itself (if it is mobile featuring a mechanism), it has other joints too along the forearm, such as a joint in the wrist and / or a joint somewhere along the forearm that could make the rotation around the longitudinal axis of the forearm.

An example of a functional prosthesis for the forearm is in Fig. 1.2 a, which has a high mobility [7]. At such prosthesis in addition to the joints of the fingers, there is a joint at the wrist. Then depending on the size of the existing forearm (the blunt area), the prosthesis can be extended, grasping in the end the rest of the existing part.

Prosthetic tools for hand, forearm and elbow, are not different from previous ones specified in prostheses for hand and forearm, as the change appears only in the actual hand (finger replacement with a "clamp").

In the case of *functional prostheses*, the complexity is higher; the prostheses present a joint at the elbow that is a classic mono mobile rotation coupling. If the elbow joint is valid, on the forearm it can be attached along the sleeve that fixes the prosthesis for the hand, a mechanism to drive this prosthesis in flexion, respectively extension of the elbow.

The elbow drive is difficult, but it can be achieved by means of wires, artificial muscles and, less frequently, by linear motors. As a functional prosthesis, the variant in Fig. 1.2 b is presented, not fixed on the rest of the arm [7]. You can see captors for bio signals and the power supply battery.



a b

Fig. 1.2 – Functional prostheses for hand and forearm (a) respectively for hand, forearm, and elbow (b).

This paper features the synthesis, the analysis, the design, and the functional simulation of a prosthesis mechanism for the human upper limb up to the median level of the arm.

The prosthesis presented in this paper, compared to the similar existing ones was designed to use relatively simple solutions, both on the mechanical structure and the drive, to get enough functionality at a cost as low as possible. In addition, at some extent, we suggest for the first time the simulation of operation in a CAD environment. The purpose is to optimize the constructive aspect, and we suggest a functional simulation in a virtual environment-VRML to explore all the possibilities of use, with the prospect of enlargement to the use of virtual simulation by the user as well, a faster learning of the prosthesis use, thus increasing the overall efficiency of its use.

2. STRUCTURAL SINTHESIS AND ANALYSIS

2.1. STRUCTURAL SYNTHESIS

The structure of the skeleton (the biological mechanism) of the human upper limb (Fig. 2.1.) is characterised by 7 mobility degrees (rotations) in the forearm and the arm area and by 20 mobility degrees only at the level of the phalanges of the hand [3, 4, 5]. A similar mechanical structure (Fig. 2.2, only the forearm and the arm area), based on the biological mechanism previously described is much too complex for a convenient technical solution, as well as for the need to ensure a minimum functionality to perform specific current activities [5].

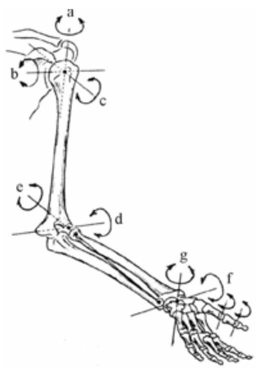


Fig. 2.1 – The biological mechanism of the human hand.

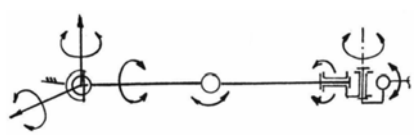


Fig. 2.2 – Reference structural scheme.

Consequently, taking into account that the prosthesis considered is limited to the median level of the forearm, one suggests a structure featuring: a rotation at the level of the wrist, a rotation at the level of the forearm and a rotation of the elbow. For the hand, one suggests a mono mobile mechanical structure with articulated fingers [6].

2.2. STRUCTURAL ANALYSIS

According to Fig. 2.3, the mechanical structure of the prosthesis has the mobility degree $M = 4$. That means: I – a rotation at the level of the elbow, performed using the engine M1. The second, II stands for a rotation at the level of the forearm, performed using the engine M2; III – a rotation at the level of the wrist, performed using the engine M3 and IV – a closing movement of the prosthesis for the hand, performed using the engine M4 – the prosthesis opens using an elastic element – a spring [3, 4].

2.2.1. Structural Analysis of the Palm

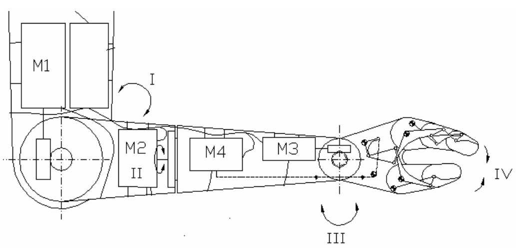


Fig. 2.3 – Structural design proposed.

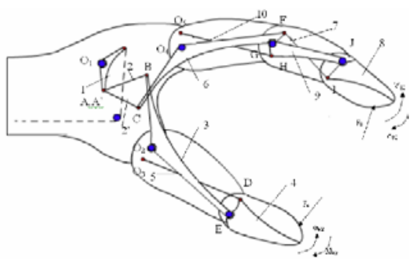


Fig. 2.4 – Structural scheme of the palm.

This version of the palm (Fig. 2.4) practically corresponds to one of the most complex structures for a prosthesis, having the thumb made of two phalanxes, and the four fingers, represented by the index finger, consisting of three phalanxes. The four fingers are driven simultaneously with the index finger and the thumb by a single engine mechanism, in which case the whole mechanism is mono mobile. This structure is close enough to the structure of the human hand.

The thumb movement is generated by two serial anti-quadrangle mechanisms made of closed kinematic chains: I (0-1-2-3-0), and II (0-3-4-5-0), where bars 3 and 5 are joint at the base (palm) in the points O2 respectively O3. The phalanx f 11, corresponds to the bar 3, and the phalanx f12 is assimilated to the bar 4, connected to the balancer 3, 5 in the points E, respectively D.

The index finger d2 comprises the anti-quadrangle III: 0-1-2-6-0, which continues, in series, with the anti-quadrangle IV: 0-6-9-10-0 and the anti-parallelogram V: 6-7-8-9.6, the bars 6 and 10 being connected to the base (palm) in the points O4, respectively in O5. The phalanx f21 corresponds to the bar 6, the phalanx f22 can be assimilated to bar 9, and phalanx f 23 is identified cinematically with bar 8, which is joint in I and J to bars 7 and 9. The degree of mobility of this mechanism is calculated with the formula [2]:

$$M = \sum_{i=I}^{V} M_i - \sum f_c = M_{\mathrm{I}} + M_{\mathrm{II}} + M_{\mathrm{III}} + M_{\mathrm{IV}} + M_{\mathrm{V}} - \sum f_c = \\ = 1+1+1+1+1-4 = 1, \tag{2.1}$$

in which according to Fig. 2.4 the results are:

$$\begin{aligned} M_{\mathrm{I}} &= \sum f_i - \chi_{\mathrm{I}} = f_{O1} + f_A + f_B + f_{O2} - \chi_{\mathrm{I}} = 1+1+1+1-3 = 1, \\ M_{\mathrm{II}} &= \sum f_i - \chi_{\mathrm{II}} = f_{O2} + f_E + f_D + f_{O3} - \chi_{\mathrm{II}} = 1+1+1+1-3 = 1, \\ M_{\mathrm{III}} &= \sum f_i - \chi_{\mathrm{III}} = f_{O1} + f_{A'} + f_C + f_{O4} - \chi_{\mathrm{III}} = 1+1+1+1-3 = 1, \\ M_{\mathrm{IV}} &= \sum f_i - \chi_{\mathrm{V}} = f_{O4} + f_G + f_H + f_{O5} - \chi_{\mathrm{V}} = 1+1+1+1-3 = 1, \\ M_{\mathrm{V}} &= \sum f_i - \chi_{\mathrm{IV}} = f_F + f_I + f_J + f_G - \chi_{\mathrm{IV}} = 1+1+1+1-3 = 1, \end{aligned} \tag{2.2}$$

$$\sum f_c = f_{O1} + f_{O2} + f_{O4} + f_G = 4. \tag{2.3}$$

The driving element of the mechanism denoted by I, has a rotating motion around the fixed base O1, turning from right to left, thus bringing finger d1 close to d2. To open the prosthesis, the elastic force of a helical spring, mounted between the element 1 and the base 0 (the palm), is used.

3. KINEMATICAL SYNTHESIS AND ANALYSIS

3.1. KINEMATICAL SYNTHESIS

The kinematical synthesis seeks to obtain the size of the main elements of the mechanical structure, which, in this case, must be as close as possible to the size of a model human arm.

Special attention must be paid while selecting the size of the hand mechanism parts, in order to ensure the right closure of the fingers.

3.2. KINEMATICAL ANALYSIS

3.2.1. Kinematic analysis of the palm

For the mechanisms with articulated bars, the general method of calculation used is *the closed vector contour method* [1]. The mechanisms used may be mono contour or poly-contour. The results obtained for mono-contour mechanisms can be easily extrapolated to the poly-contour mechanisms. For the calculation of the transmission functions, the two fingers will be taken separately, namely the thumb, and the index finger respectively.

The **thumb** being composed of two phalanxes, it is made of a poly-contour mechanism. To simplify the calculations, the mechanism can be reduced to two mono contour mechanisms corresponding to each phalanx.

a. Transmission function calculation for position. According to Fig. 2.4 the vector outline of the anti-quadrangle mechanism (anti-parallelogram) $O1ABO2$ is $O1A + AB + BO2 + O2O1 = 0$. The position input parameter is the angle φ_{10}, and the position output parameter is the angle φ_{11}. The function that transmits the position is $\varphi_{11} = \varphi_{11}$ (φ_{10}, l_1, l_2, l_{30}, l_{31}), where l_1, l_2, l_{30}, l_{31} are the linear dimensions of the elements.

For the mono contour mechanism $O2O3DE$ under Fig. 2.4, the vector contour closing equation is: $\overrightarrow{O_2O_3} + \overrightarrow{O_3D} + \overrightarrow{DE} + \overrightarrow{EO_2} = \vec{0}$. The position input parameter is the angle φ_{21}, and the position output parameter is the angle φ_{41}. The transmission function for the position is: $\varphi_{41} = \varphi_{41}$ (φ_{21}, l_{50}, l_5, l_{41}, l_{32}), where l_{50}, l_5, l_{41}, l_{32} are the linear dimensions of the elements.

b. Calculation of velocity transmission function. The function of the velocity transmission $\omega_{41} = \omega_{41}$ (φ_{10}, ω_{10}) is obtained by derivation with respect to time, of the expressions for the transmission function, of the positions for each mono contour mechanism, and the introduction of connections between the output speed, of a mechanism and the input speed, into the following mechanism. Based on the angular velocity ω_{41} you can get the linear velocity of the point P_4 of the last phalanx, from the equation: $V_{P4} = \omega_{41}\ EP_4$ (Fig. 2.4).

c. Calculation of the transmission function of accelerations. The transmission function of accelerations $\varepsilon_{41} = \varepsilon_{41}$ (φ_{10}, $\omega_{10,}$ ε_{10}) is obtained by a new derivation of expressions in relation to the time, obtained at point **b,** and by introducing of connection between the specific parameters of the two mechanisms.

The **index finger** consists of a poly-contour mechanism, with articulated bars, consisting of three phalanxes. As for the thumb, it will also be calculated separately for three mono contour mechanisms, specific for each phalanx. The general scheme of the index finger is represented in Fig. 2.4. As initial data, the linear dimensions of the elements are known, as well as the constructive angles and the external independent parameters.

a. Calculation of the transmission function of the positions. The xO_1y reference system is considered and the method of closing vector contour equation is applied for each mono-contour mechanism. The transmission function of the positions is $\varphi_{81} = \varphi_{81}(\varphi_{10})$. For the mono contour mechanism $O_1A'CO_4$ according to Fig. 3.1.a we get to the closing equation:

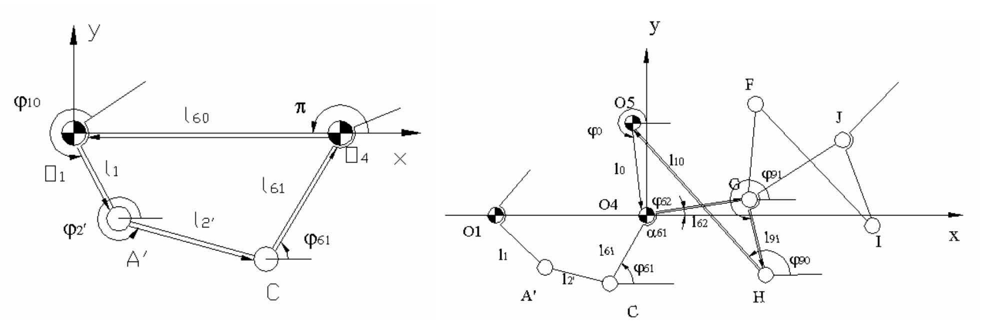
$$\overrightarrow{O_1A'} + \overrightarrow{A'C} + \overrightarrow{CO_4} + \overrightarrow{O_4O_1} = \vec{0}\,. \tag{3.1}$$

The input parameter is the angle φ_{10}, and the output parameter is the angle φ_{61}. The position transmission function is in implicit form: $\varphi_{61} = \varphi_{61}$ (φ_{10}, l_1, $l_{2'}$, l_{61}, l_{60}).

For the mono contour mechanism O_4GHO_5 according to Fig. 3.1,b the vector contour closing equation is:

$$\overrightarrow{O_4G} + \overrightarrow{GH} + \overrightarrow{HO_5} + \overrightarrow{O_5O_4} = \vec{0} \tag{3.2}$$

in the reference system xO_4y.



a b

Fig. 3.1 – Structural scheme ($O_1A^{'}CO_4$ –a, O_4GHO_5–b).

For the last mono contour mechanism (*GIJF*) according to Fig. 3.2 the vector contour closing equation is:

$$\overrightarrow{GJ} + \overrightarrow{JI} + \overrightarrow{IF} + \overrightarrow{FG_4} = \vec{0}\,. \tag{3.3}$$

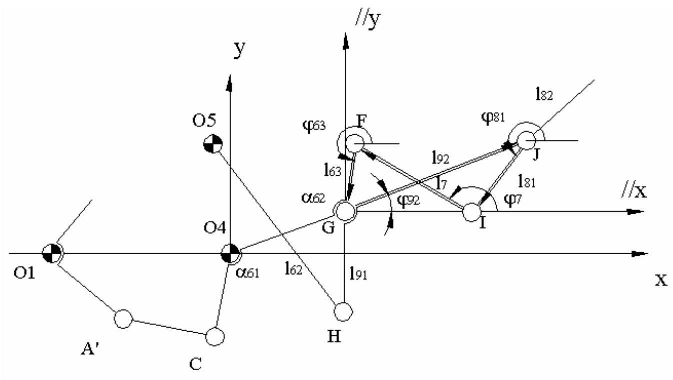


Fig. 3.2 – Structural scheme (*GIJF* contour).

After calculations, we get to the velocity transmission function $\varphi_{81} = \varphi_{81}(\varphi_{10}, l_1, l_{2'}, l_{61}, l_{60\,...})$.

b. Velocity transmission function calculation. The velocity transmission function $\omega_{81} = \omega_{81}$ $(\varphi_{10}, \omega_{10})$ is obtained by derivation with respect to time, of the expressions for the transmission of the positions, for each mono contour mechanism and the introduction of relations between output speed of a mechanism and input speed in the next mechanism. Based on the angular velocity ω_{41} we get to the linear velocity of the point P_4 on the last phalanx using the equation: $V_{P8} = \omega_{81}$, JP_8 (Fig. 2.4).

c. Accelerations transmission function calculation. The accelerations transmission function $\varepsilon_{81} = \varepsilon_{81}$ $(\varphi_{10}, \omega_{10,} \varepsilon_{10})$ is obtained by a new derivation of the expressions obtained at point **b** in relation to the time and the introduction of relationships between specific parameters of the two mechanisms.

3.2.2. Kinematical analysis of the forearm – elbow unit

The kinematical analysis is performed using the method of the homogenous operators to solve the problem of the direct kinematics: getting the position of the characteristic point at the level of the palm according to the driving movements.

The ***cinematic stage*** includes the following operations (according to Fig. 3.3):

0. Stating initial data:
   - We know the geometric elements of the structure (elements length l_1, l_2, l_3; weight centres position c_{11}, c_{22}, c_{33});
   - We know the functions describing movements in the couples $q_1 = q_1(t)$, $q_2 = q_2(t)$, $q_3 = q_3(t)$;
   - We know transformation matrices from the local reference systems in the global one, respectively from the global one in the local reference systems A_{01}, A_{02}, A_{03}, A_{10}, A_{20}, A_{30};
1. Weight centres accelerations calculation (in local reference systems and in the global reference system):
   - The position vector of weight centres is determined, reported to the global reference system (R_1, R_2, R_3);
   - Weight centres accelerations are determined, in the global reference system, deriving the determined position vector (R_{1pp}, R_{2pp}, R_{3pp});
   - One transforms, through the transformation matrices, the accelerations from the global reference systems in local ones (each acceleration in the local system of the corresponding element r_{1pp}, r_{2pp}, r_{3pp});
2. Angular velocity and accelerations calculation (in local reference systems):

- One determines the relative angular velocity of each element in the basic system Ω_{10}, Ω_{20}, Ω_{30};
- One determines, through vector sum, the absolute angular velocity of each element W_1, W_2, W_3;
- By deriving the absolute angular velocity of each element one obtains the absolute angular acceleration E_1, E_2, E_3;
- One transfers absolute angular velocity and accelerations in local corresponding references ω_1, ω_2, ω_3; ε_1, ε_2, ε_3.

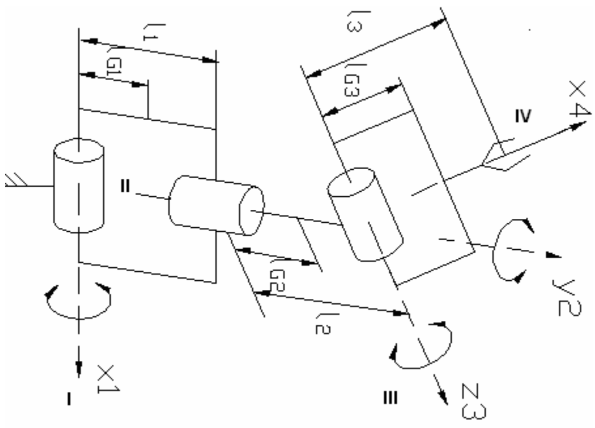


Fig. 3.3 – Kinematical design.

According to Fig. 3.3, the position of the characteristic point, linked to the palm, is given by the following matrix-like relationship:

$$A_{04} = A_{01} A_{12} A_{23} A_{34}, \tag{3.4}$$

in which the transfer matrices A_{ij} are the passage matrices from the system of coordinates j to the system of coordinates i, related to the element j, respectively to the element i [1]. Each A_{ij} matrix is obtained using one operator of translation and/or one operator of rotation. For a translation from the reference system m to the reference system n, the matrix of translation operator (Fig. 3.4a) is T^x_{mn} and the operator of rotation around x (Fig. 3.4b) axis is R^x_{mn}:

$$A_{mn} = T^x_{mn} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ d_{nm} & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}; \quad A_{mn} = R^x_{mn} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & C_{nm} & -S_{nm} \\ 0 & 0 & S_{nm} & C_{nm} \end{bmatrix}.$$

The matrix for the operator of rotation around y axis is (Fig. 3.4c):

$$A_{mn} = R_{mn}^{y} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & C_{nm} & 0 & S_{nm} \\ 0 & 0 & 1 & 0 \\ 0 & -S_{nm} & 0 & C_{nm} \end{bmatrix};$$

around z axis is (Fig. 3.4d): $A_{mn} = R_{mn}^{z} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & C_{nm} & -S_{nm} & 0 \\ 0 & S_{nm} & C_{nm} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$

In these matrices $S_{nm}= \sin\varphi_{nm}$, and $C_{nm}= \cos\varphi_{nm}$.

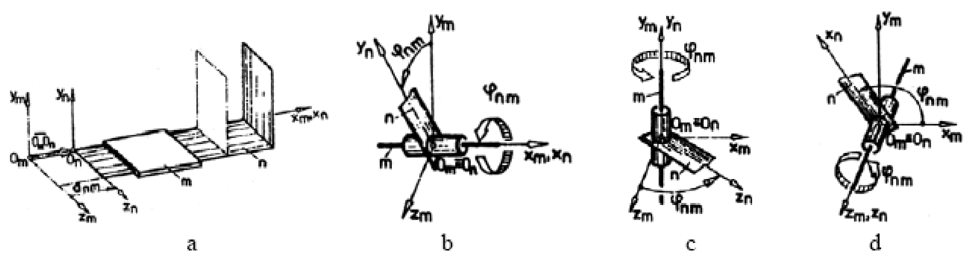


Fig. 3.4 – Cinematic modules.

The compound operators will be $A_{01} = R_{01}^{x}\, T_{01}^{Y}$; $A_{12}= R_{12}^{y}\, T_{12}^{Y}$; $A_{23}= R_{23}^{z}$; $A_{34}= T_{34}^{x}$, with the following specific forms of the rotation and translation operators:

$$R_{01}^{x} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & C_{10} & -S_{10} \\ 0 & 0 & S_{10} & C_{10} \end{bmatrix} \qquad T_{01}^{y} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ d_{10} & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$R_{12}^{y} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & C_{21} & 0 & S_{21} \\ 0 & 0 & 1 & 0 \\ 0 & -S_{21} & 0 & C_{21} \end{bmatrix}$$

$$T_{12}^{y}=\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ d_{21} & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}\qquad R_{23}^{x}=\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & C_{32} & -S_{32}\\ 0 & 0 & S_{32} & C_{32}\end{bmatrix}$$

$$T_{34}^{y}=\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ d_{34} & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}.$$

In these matrices: $C_{10}=\cos\varphi_{10}^{x}$; $S_{10}=\sin\varphi_{10}^{x}$; $d_{10}=l_1$; $C_{21}=\cos\varphi_{21}^{y}$; $S_{21}=\sin\varphi_{21}^{y}$; $d_{21}=l_2$; $C_{32}=\cos\varphi_{32}^{x}$; $S_{32}=\sin\varphi_{32}^{x}$; $d_{34}=l_3$; i = 0,1,2,3,4; the angles φ_{ij}^{k} are the angles between the reference systems i and j and l_i are the distances between the reference systems with parallel axes.

4. DYNAMIC ANALYSIS

Dynamic analysis includes the following steps:

a. Stating initial data:
   - Inertial parameters of the structure elements (elements weight m_1, m_2, m_3, inertial matrices of elements J_1, J_2, J_3);
   - External forces and momentum that activate elements F_{ext1}, F_{ext2}, F_{ext3}; M_{ext1}, M_{ext2}, M_{ext3};
   - Transformation matrices between local reference elements A_{32}, A_{21}, A_{10};
   - Weight centres accelerations, angular velocity and accelerations of the elements r_{1pp}, r_{2pp}, r_{3pp}; ω_1, ω_2, ω_3; ε_1, ε_2, ε_3;

b. From the element on the top of the cinematic chain one determines, based on Newton's equations, the reactions in the downstream couple;

c. On the basis of the action and reaction principle and using the transformation matrices between local reference systems, one changes these reactions in the reference system of the downstream element;

d. Previous stages are covered for all the elements of the structure;

e. Generalized forces in the couples are identified.

The dynamic study involves estimating the weight and then the momentum generated sequentially starting from the element 3 to 1, in order to estimate in the end the driving motors necessary power.

For the element 3 weight will be expressed in the local system.

$$ {}^{3}\vec{G}_3 = a_{03}^{t}\,{}^{0}\vec{G}_3 = \begin{bmatrix} -g\left(-\cos(\varphi_{10})\sin(\varphi_{21})\cos(\varphi_{32}) + \sin(\varphi_{10})\sin(\varphi_{32})\right) \\ g\left(\cos(\varphi_{10})\sin(\varphi_{21})\sin(\varphi_{32}) + \sin(\varphi_{10})\cos(\varphi_{32})\right) \\ -\cos(\varphi_{10})\cos(\varphi_{21})\cdot g \end{bmatrix}. \quad (4.1) $$

The force occurring in the couple is F_{323} and it is the result of the equation:

$$ {}^{3}F_{32} = m_3\,{}^{3}a_{G3} - {}^{3}G_3. \quad (4.2) $$

The basic momentum occurring in the couple 3 is:

$$ {}^{3}\vec{M}_3 = J_{G3}\,{}^{3}\vec{\varepsilon}_3 + {}^{3}\tilde{\omega}_3 J_{G3}\,{}^{3}\vec{\omega}_3. \quad (4.3) $$

Completed by a momentum that is given by the force in the couple, which is F_{323}

$$ {}^{3}\vec{M}_3 = {}^{3}\vec{M}_{32} + R_3 \times {}^{3}\vec{F}_{32}. \quad (4.4) $$

Therefore, the total momentum occurring in the third couple is M_{323} obtained from the equality between the two equations, as follows:

$$ {}^{3}\vec{M}_{32} = J_{G3}\,{}^{3}\vec{\varepsilon}_3 + {}^{3}\tilde{\omega}_3 J_{G3}\,{}^{3}\vec{\omega}_3 - R_3 \times {}^{3}\vec{F}_{32}, \quad (4.5) $$

where J_{G3} = inertia matrix;

$$ J_{G3} = \begin{bmatrix} J_3 & 0 & 0 \\ 0 & J_3 & 0 \\ 0 & 0 & J_3 \end{bmatrix}, \quad (4.6) $$

and ω_{33} is the vector multiplication result associated to ω_{33}.

As a result, the motor momentum in the couple 3 will be:

$$ \tau_3 = {}^{3}\Delta_3\,{}^{3}M_{32} = {}^{3}M_{32}^{z}, \quad (4.7) $$

where Δ_{33} is:

$$ {}^{3}\Delta_3 = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}. \quad (4.8) $$

Similar we will calculate for the element 2 and element 1.

For numerical calculations, one adopts a proper size for the prosthesis elements. Taking as model the human hand the sizes will be similar to it. Data are listed in the following table (Table 4.1):

Table 4.1

Numerical data

Weight	Length	Inertia momentum
$m_1 = 0.35$ kg	$l_1 = 0.078$ m	$J_1 = 1.061$ kg · m^2
$m_2 = 0.9$ kg	$l_2 = 0.142$ m	$J_2 = 2.26$ kg · m^2
$m_3 = 6.7$ kg	$l_3 = 0.15$ m	$J_3 = 6.828$ kg · m^2
	$l_{G1} = l_1 / 2 = 0.039$ m	
	$l_{G2} = l_2 / 2 = 0.07$ m	
	$l_{G3} = l_3 / 2 = 0.075$ m	

One considers the gravitational acceleration as equal to 9.81 m/s^2 and one specifies the trajectory figured out in the task area. The link between the performer trajectory and the corresponding variation of the angles in couples is established on cinematic bases and then the proper calculation is completed. To resolve this problem we will use *the method of interpolation polynomials.* It aims to transform the vectors obtained in time-dependent functions, which meet the initial and final conditions concerning the speed and consider the maximum values of the accelerations.

If the task is to get from one point to another point (without imposing other conditions concerning the shape of the trajectory between the two points), which is the current case, for the interpolation, you can use a 3-degree polynomial:

$$q_i(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3, \tag{4.9}$$

where the unknown values a_0, a_1, a_2, a_3 are obtained based on the following conditions:

– at the moment $t = 0$

$$\begin{aligned} q_i(0) &= q_{i1} = a_0, \\ \dot{q}_i(0) &= \dot{q}_{i1} = a_1, \end{aligned} \tag{4.10}$$

– at the moment $t = T$, where T is the duration of the movements (the same in both areas) – in our case $T = 10$

$$\begin{aligned} q_i(T) &= q_{i2} = a_0 + a_1 T + a_2 T^2 + a_3 T^3, \\ \dot{q}_i(T) &= \dot{q}_{i2} = a_1 + a_2 T + a_3 T^2. \end{aligned} \tag{4.11}$$

Using the above relations in case the initial and final speeds are zero we obtain the following results:

$$a_1 = 0, \quad a_3 = -\frac{2}{T^3}\left(q_f - q_i\right), \quad a_2 = \frac{3}{T^2}\left(q_f - q_i\right), \; a_0 = q_{i1}. \tag{4.12}$$

In our case, motion in couples represent the angular position, φ_{10}, φ_{21}, φ_{32}, the angular speed ω_{10}, ω_{21}, ω_{32} respectively angular acceleration ε_{10}, ε_{21}, ε_{32}, After replacement of each variable separately we will get the trajectory desired as the engine momentum, time-dependant, represented for all the three couples in the joints in Fig. 4.1.

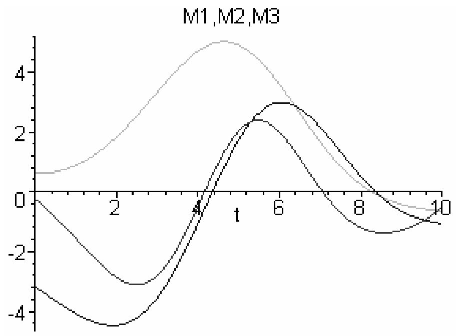
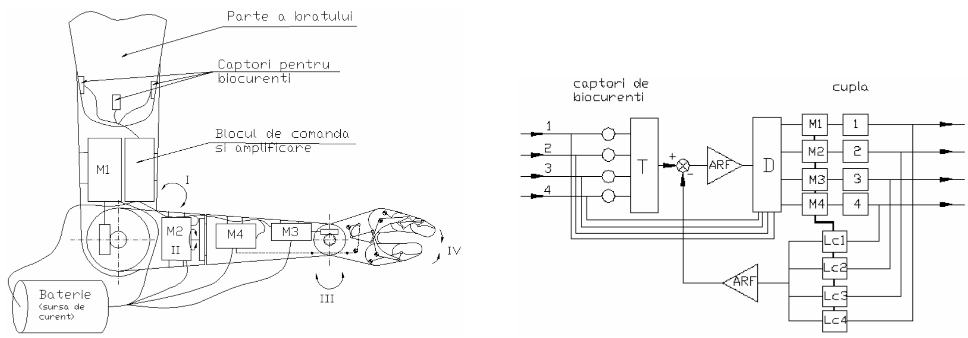


Fig. 4.1 – Motor momentum variation M_1, M_2, M_3 necessary according to time.

5. CONSTRUCTIVE DESIGN

The constructive design was performed assuming that electrical engines driven by bioelectricity would be used, and it would be trapped from the neuronal system, which should control the muscles in that area of the arm, which is replaced by the prosthesis (Fig. 5.1a) [7]. A general design of the prosthesis control system is described in Fig. 5.1b, in which the symbols have the following meanings: L_C – detent; T – transducer; M – motor; ARF – amplification block (recovery, filtering); D – decoder; 1, 2, 3, 4 – bioelectricity captors.



a b

Fig. 5.1 – General construction (a) and control scheme (b).

Based on the resistance calculations, taking into consideration the loading forces of the elements, assuming a seizing force of ~ 8 daN, one has performed a technical project represented in Fig. 5.2.

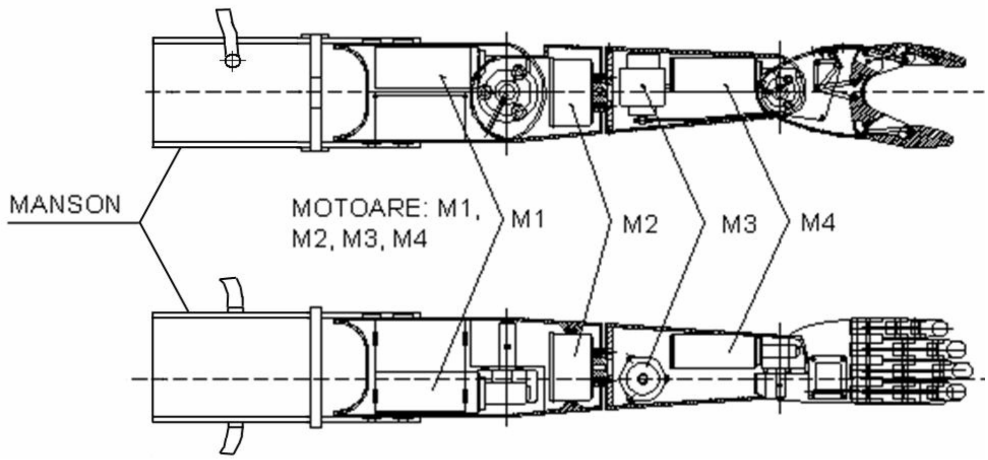


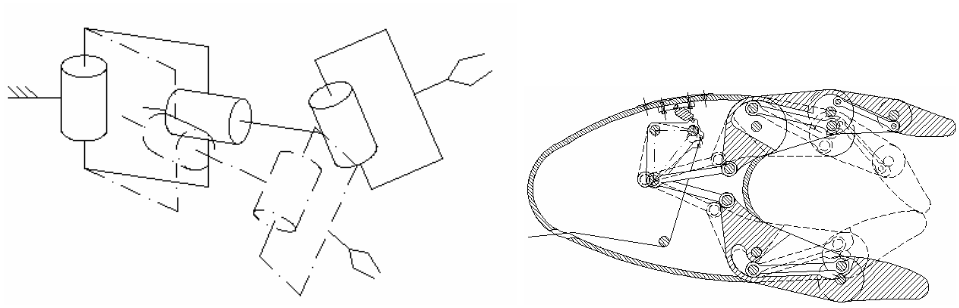
Fig. 5.2 – Technical design of the prosthesis.

In this case, there are some main constructive particularities. First, there is the elbow rotation performed by a motor reducer equipped with a worm – spiral wheel mechanism. The forearm rotation is performed by an interior gear wheel – wheel. The wrist rotation is performed as well using a motor reducer equipped with a worm – spiral wheel gear, and the fingers closure is performed by pulling a thread, which is coiled on a reel by the engine M4 [4].

6. FUNCTIONAL SIMULATION

6.1. SIMULATION OF SCHEMATIC PERFORMANCE

One first functional simulation is accomplished by the schematic representation. For the three couples there were presented schematically two movements of the arm where can be observed the relative movements of each coupling (Fig. 6.1a). We represented cinematically for the palm the open and closed scheme (Fig. 6.1b). The simulation of the motion for the hand (palm) was realized using the software FLASH representing as distinctly as possible the relative movement of each element.

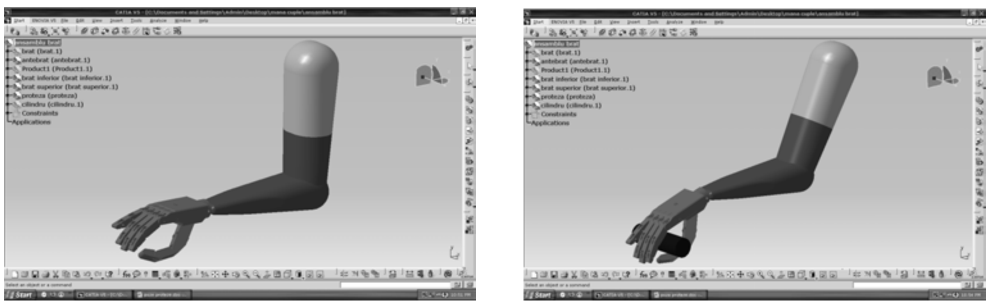


a b

Fig. 6.1 – Schematic functional simulation.

6.2. CAD AND VRML FUNCTIONAL SIMULATION

For the CAD functional simulation of the prosthesis there was made a model in CATIA (Fig. 6.2) which highlights the three mobility degrees at the level of the forearm and the mobility corresponding to the hand closure. The functional simulation allows checking the access in the work area, the highlight of the limit configurations etc.

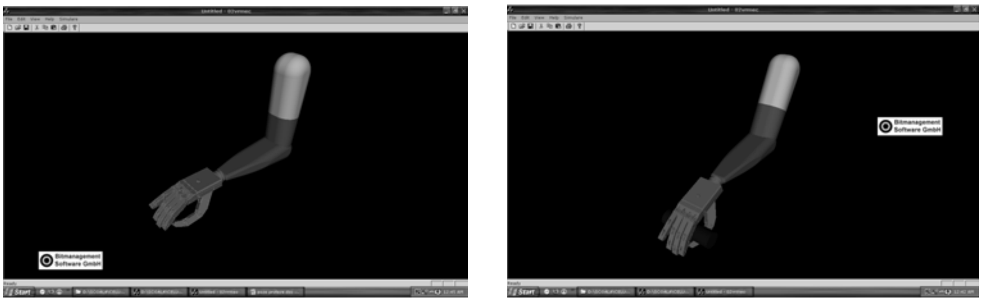


a b

Fig. 6.2 – Modelling and simulating of prosthesis in CATIA.

The model in CATIA has been transposed in the virtual environment VRML (Fig. 6.3) in order to be applied for practising the use of the prosthesis by the beneficiary.

In this stage, the functional simulation in virtual environment has been performed only for the hand using a CYBER GLOVE, based on the scheme in Fig. 6.4, where the CYBER GLOVE can be seen, controlled by the human operator, the interface blocks, and the virtual prosthesis.



a b

Fig. 6.3 – Simulation of prosthesis use in VRML.

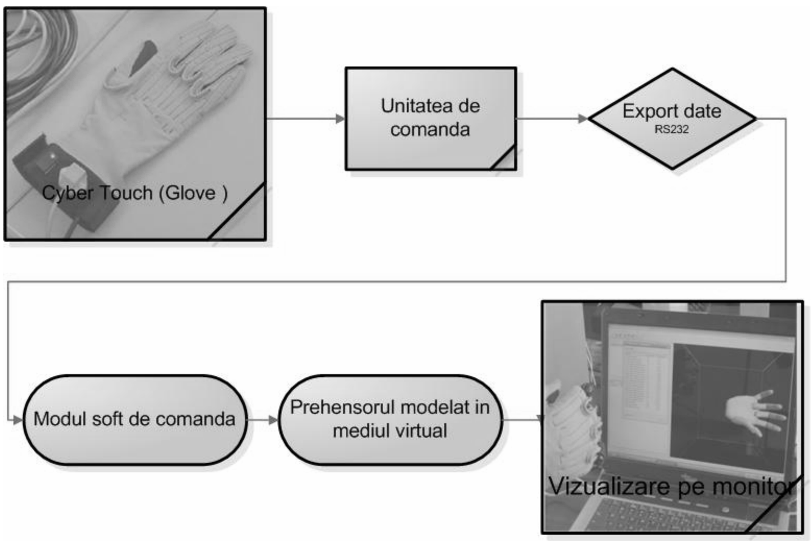


Fig. 6.4 – Interface scheme between CYBER GLOVE and virtual prosthesis.

The procedure used in the case of simulation in virtual environment of the prosthesis for the palm will be applied in a similar way to the entire prosthesis designed.

7. CONCLUSIONS

Based on the aspects featured in this paper one can draw the following conclusions:

1. The prostheses for the human upper limb are based on a mechanical structure more or less similar to the biological mechanism corresponding to the human hand.

2. The mechanical structures used can as well have a relatively reduced complexity under the condition to ensure a sufficient functionality for the strictly necessary operations.

3. The synthesis and the analysis of the mechanical structures suggested are performed using well-known methods from the classical theory of mechanisms.

4. The simulation in CAD (CATIA) environments and/or in virtual environment (VRML) is useful to improve the constructive solution, respectively to facilitate the learning of the beneficiary to use the prosthesis.

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