# ABOUT THE KINEMATICS AND CONTROL SYSTEM OF AN ANTHROPOMORPHIC HAND USABLE AS PROSTHESIS

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*In această lucrare sunt discutate principalele etape ale construcției unei mâini artificiale, punându-se accent pe procesul de fabricație al componentelor ce constituie mâna şi pe sistemul de control al acesteia care este bazat pe componente mecatronice de ultimă generație. O altă problemă tratată în această lucrare este cinematica directă a mâinilor antropomorfe, fiind dată şi o metodă teoretică de rezolvare a acesteia.*

*This paper deals with the issues concerning the main stages of an artificial hand construction with emphasis on the fabrication process and hand control system based on latest generation of mechatronic components. A method of solving the direct kinematic problem is another topic of this paper.*

**Keywords:** prosthetic device, kinematics, control

## 1. Introduction

The anthropomorphic hands represent the response of the scientific community in the pursuit of constructing artificial devices similar with the human hand in terms of overall performance: replicating the exact movements and their amplitudes (kinematic structure), force capabilities, visual appearance (shape, dimensions), mass, etc. Therefore, a model for an AH is made by similarity with the natural model of the hand. The applications of the anthropomorphic hands can be found in medical field as prosthetic devices [1, 2] or in robotics as end effectors for robotic arms [3- 10].

Human hand consists of a palm and five fingers (thumb, index, middle, ring and little finger), see Figure 1. The thumb is made of two phalanxes, with 3 D.O.F., while the other fingers are made from three phalanxes and 4 D.O.F. Therefore, an equivalent model of the human hand must have 19 D.O.F. Having said that, to be compared to the human hand, an artificial hand must be equipped with a complex mechanical model which leads to difficulties in terms of actuation, gauge, mass, aesthetics, control, etc.

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Solving partially or totally the problems described above, often leads to expensive prosthetic devices that minimizes the chances for common patients which do not have material resources. A simple way of approaching the development of a modern, cost effective prosthetic device for the human hand is to simplify the mechanical model. Furthermore, to simplify the problem even more not all the joints are directly actuated (the number of actuators is smaller than the number of degrees of freedom of the mechanical model), resulting a so called underactuated artificial hand [11].

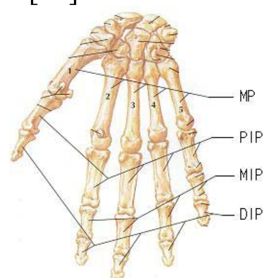


Fig. 1 The mechanical model of the human hand [12]

## 2. Fabrication of the artificial hand

This paper presents a newly developed anthropomorphic hand (AH) which can be used as prosthesis for the patients with amputated hands. The hand has three fingers (a thumb with two phalanxes and two identical fingers with three phalanxes) and a palm.

The basic steps of construction of the AH are shown next. We began constructing the virtual models of the phalanxes and palm in SolidWorks. Afterwards, the hand assembly was defined. Simulations have been performed in order to confirm the correct closing of the fingers with or without object grasping (see Fig. 2). The parts needed to construct the hand have been fabricated directly from the 3D models by Rapid Prototyping Method using a 3D Zcorp printer (Fig.3).

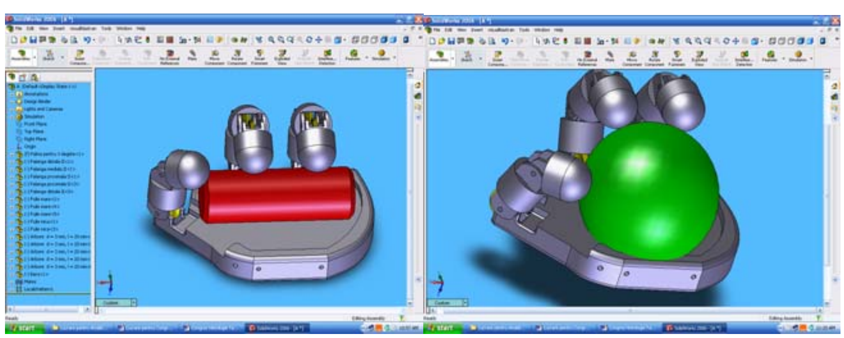

Fig. 2 – Simulations of object grasping

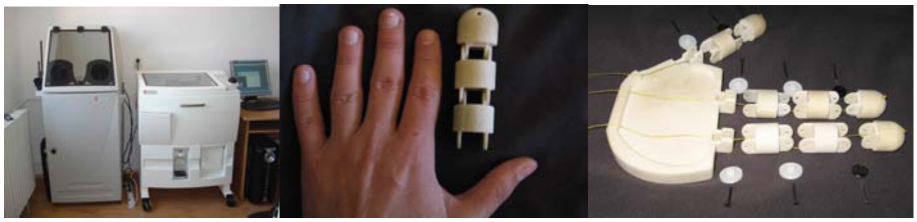

Fig. 3 – The 3D Zcorp printer used for fabricating the parts (left); finger and hand pictures before making the assembly (right)

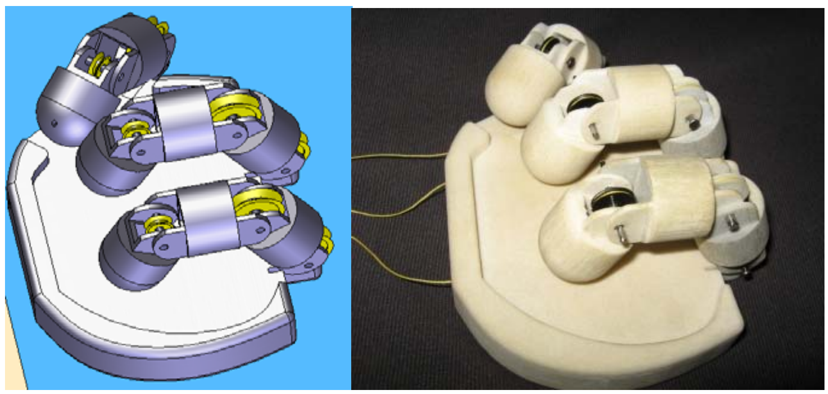

Fig. 4 – The resulted artificial hand (3D prototype vs. real)

## 3. Kinematics of the new artificial hand

Kinematics studies the motion without considerations of the forces that produce it. To understand different types of Kinematics, it is necessary to describe Forward and Inverse Kinematics. Forward Kinematics refers to the direct manipulation of the structure through rotations and translations until it reaches the desired final position. Thereby, in the case of an artificial hand solving the Forward Kinematics problem is equivalent to finding the coordinates of the finger tips as a function of the joint angles: $x = f(\phi)$, where $x$ is the coordinates vector of the finger tips and $\phi$ - joint angles vector. Conversely, solving the Inverse Kinematics problem assumes finding the joint angles in relation to the known position of the finger tips. The last problem is much difficult to solve considering that, in general, artificial hands are hyper redundant robotic systems (the degree of freedom of the mechanical model is bigger than the number of degrees of freedom that should be suppressed in order to immobilize an object) [13].

In this paper, we analyze the Forward Kinematics problem for a 3 D.O.F. anthropomorphic finger, which is the case of the constructed finger prototype (see Figs. 3 and 4):

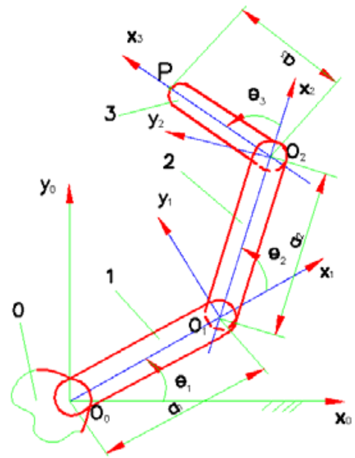


Fig. 5 – A 3 D.O.F anthropomorphic finger according to Denavit-Hartenberg formalism

We used the Denavit – Hartenberg method [14] which is a general method for analyzing the kinematics in robotics. According to D-H formalism it is possible to link two different coordinate frames by calculating the transformation matrix between them. This matrix is always a function of four parameters denoted with $\alpha_{i-1}$, $a_{i-1}$, $\theta_i$ and $d_i$, also called D-H parameters. The finger movement is in a single plane (the joint axes are always paralell during the flexion-extension motion) so $\alpha_{i-1} = 0$ for $i = \overline{1,3}$. In addition, the $d_i$=0 for $i = \overline{1,3}$, because the finger has only revolute joints. Therefore, the remaining D-H parameters are the angles between phalanxes axes denoted with $\theta_i$ and the lengths of the phalanxes denoted with $a_{i-1}$.

*Table 1*

**The Denavit-Hartenberg kinematic parameters for a 3 D.O.F. finger**

| Element | $\alpha_{i-1}$ [°] | $a_{i-1}$ [mm] | $\theta_i$ [°] | $d_i$ [mm] |
|---|---|---|---|---|
| 1 | 0 | $a_1$=35 | $\theta_1$ | 0 |
| 2 | 0 | $a_2$=35 | $\theta_2$ | 0 |
| 3 | 0 | $a_3$=32 | $\theta_3$ | 0 |

The coordinates of P with respect to the reference frame $O_0\ x_0\ y_0\ z_0$ :

$$[r_0] = [H] \cdot [r_2] \tag{1}$$

, [H] is the global transformation matrix from the reference frame $O_0\ x_0\ y_0\ z_0$ to the $O_2\ x_2\ y_2\ z_2$ frame and $[r_2]$- position vector of the P point in $O_2\ x_2\ y_2\ z_2$ frame.

For a system with n connections, the global transformation matrix is given by:

$$H=\prod_{i=1}^{n}{}^{i-1}T_i={}^{0}T_1\cdot{}^{1}T_2\cdot\ldots\cdot{}^{n-1}T_n \tag{2}$$

In the case considered in Fig. 5, $n=2$ and $H=\prod_{i=1}^{2}{}^{i-1}T_i={}^{0}T_1\cdot{}^{1}T_2$ (3)

Next, the intermediary transformation matrices ${}^{0}T_1$ and ${}^{1}T_2$ are calculated. The $O_1\ x_1\ y_1\ z_1$ frame differs from the reference frame $O_0\ x_0\ y_0\ z_0$ by a rotation with $\theta_1$ angle over z axis and by a translation with $a_1$ along $x_1$ axis:

$${}^{0}T_1=\begin{bmatrix}\cos\theta_1 & -\sin\theta_1 & 0 & 0\\ \sin\theta_1 & \cos\theta_1 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}\cdot\begin{bmatrix}1 & 0 & 0 & a_1\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}=\begin{bmatrix}\cos\theta_1 & -\sin\theta_1 & 0 & a_1\cos\theta_1\\ \sin\theta_1 & \cos\theta_1 & 0 & a_1\sin\theta_1\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix} \tag{4}$$

In a similar manner we can calculate the transformation matrix ${}^{1}T_2$:

$${}^{1}T_2=\begin{bmatrix}\cos\theta_2 & -\sin\theta_2 & 0 & 0\\ \sin\theta_2 & \cos\theta_2 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}\cdot\begin{bmatrix}1 & 0 & 0 & a_2\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}=\begin{bmatrix}\cos\theta_2 & -\sin\theta_2 & 0 & a_2\cos\theta_2\\ \sin\theta_2 & \cos\theta_2 & 0 & a_2\sin\theta_2\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix} \tag{5}$$

It results:

$$H=\begin{bmatrix}\cos(\theta_1+\theta_2) & -\sin(\theta_1+\theta_2) & 0 & a_2\cos(\theta_1+\theta_2)+a_1\cos\theta_1\\ \sin(\theta_1+\theta_2) & \cos(\theta_1+\theta_2) & 0 & a_2\sin(\theta_1+\theta_2)+a_1\sin\theta_1\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix} \tag{6}$$

$$[r_0]=\begin{bmatrix}x_{P0}\\ y_{P0}\\ z_{P0}\\ 1\end{bmatrix}=\begin{bmatrix}\cos(\theta_1+\theta_2) & -\sin(\theta_1+\theta_2) & 0 & a_2\cos(\theta_1+\theta_2)+a_1\cos\theta_1\\ \sin(\theta_1+\theta_2) & \cos(\theta_1+\theta_2) & 0 & a_2\sin(\theta_1+\theta_2)+a_1\sin\theta_1\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}\cdot\begin{bmatrix}x_{P2}\\ y_{P2}\\ z_{P2}\\ 1\end{bmatrix} \tag{7}$$

The solutions of the direct kinematic problem are given by the following formulae:

$$\begin{cases}x_{P0}=x_{P2}\cos(\theta_1+\theta_2)-y_{P2}\sin(\theta_1+\theta_2)+a_2\cos(\theta_1+\theta_2)+a_1\cos\theta_1\\ y_{P0}=x_{P2}\sin(\theta_1+\theta_2)+y_{P2}\cos(\theta_1+\theta_2)+a_2\sin(\theta_1+\theta_2)+a_1\sin\theta_1\\ z_{P0}=z_{P2}\end{cases} \tag{8}$$

where $x_{P2} = a_3 \cos\theta_3$; $y_{P2} = a_3 \sin\theta_3$; $z_{P2} = z$ give the position and orientation of the tip of the finger (point P) with respect to the $O_2\ x_2\ y_2\ z_2$ frame. The phalanxes have the following lengths: $a_1 = 35$ mm, $a_2 = 35$ mm, $a_3 = 32$ mm. The movement limits are: $\theta_1 = 0 \div 120^{\circ}$, $\theta_2 = 0 \div 90^{\circ}$, $\theta_3 = 0 \div 45^{\circ}$.

Assuming that at the t moment the $\theta_i$ angles are the same, one can obtain the diagrams which express the connection between the position of the point P (finger tip ) given by Cartesian coordinates $x_P$, $y_P$ and the joint angles $\theta_i$, $i = \overline{1,3}$ (see Figs. 6, 7 and 8).

A similar aproach could be used to study the kinematics of the thumb, which posesses only 2 D.O.F.

The authors need to specify that these are theoretically obtained results which, in the future, will be certified by experimental research related to kinematics of this model. For this purpose, we intend to use SimiMotion video processing software (www.simi.com), which is a useful tool in experimental motion analysis.

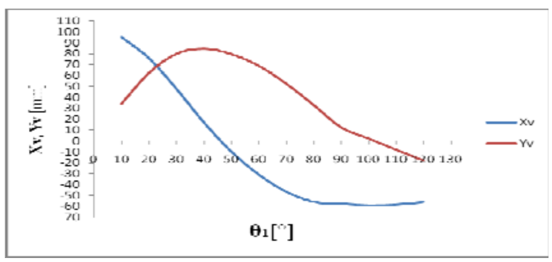


Fig. 6 – The coordinates of the finger tip as a function of $\theta_1$ angle

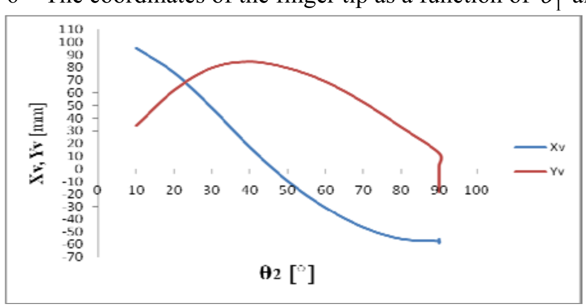


Fig. 7 – The coordinates of the finger tip as a function of $\theta_2$ angle

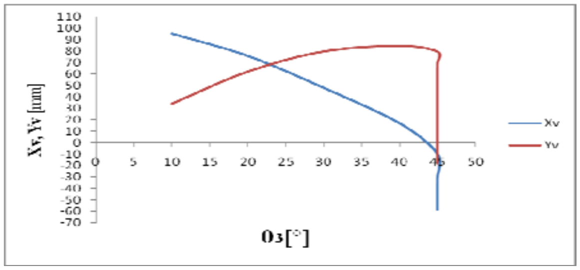


Fig. 8 – The coordinates of the finger tip as a function of $\theta_3$ angle

## 4. Control system

A modern control strategy should benefit from the latest achievements in mechatronics: microprocessors, actuators, sensors, etc. At the Faculty of Mechanics, Craiova we considered all these prerequisites in order to have an intelligent control system for the new artificial hand.

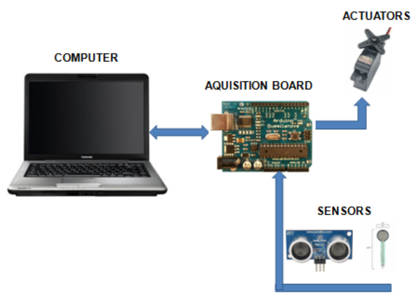


Fig. 9 – The components of control system

The goal was to have a computer based control system which enabled us to obtain either an automatic or a manual control for the hand.

For this task we used a notebook, an acquisition board, a breadboard, potentiometers, DC servomotors, etc.

Using the computer, we have created intelligent control algorithms which enable the acquisition board to drive, using Pulse Modulation Method, three DC servomotors (one for each finger) which in turn will tension the cables routed on three pulleys and connected to the distal phalanx. The control system allows smooth movement of the phalanxes down to increments of ±1°, good force capabilities and upgrade possibility by adding various sensors. In the future, force sensors mounted on each finger and an ultrasonic proximity sensor mounted in the palm will enhance the exteroceptive capabilities of the new artificial hand. Intelligent control algorithms will be created in relation to the signals from the sensors. For example, using the ultrasonic sensor we could create a program which will order the hand to grasp an object if the distance between palm and object is 2 cm. In a similar manner we could create a force control algorithm which will have as a variable the force between the phalanxes and the grasped object.

## 5. Conclusions

The main conclusions of this research are:

a) Artificial hands are designed by similarity with the human hand;
b) The Denavit-Hartenberg Method is a general method for solving the Forward Kinematics of any artificial hand;
c) Rapid Prototyping Method is a modern, fast, accurate method of obtaining any prototype;
d) The control systems of modern anthropomorphic hands rely on latest achievements in mechatronics: microprocessors, sensors, actuators, etc.
e) The new artificial hand described in this paper can be used as prosthesis for the human hand by enhancing the proprioceptive and exteroceptive sensory system.

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