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MODELING THE MOTION OF THE HUMAN HAND

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ABSTRACT

This paper presents the kinematic model of the human hand, the geometrical parameters obtained based on Denavit-Hartenberg convention, and the constraints to which the model was submitted in order not to make arbitrary gestures. Also, the paper presents the motion study using MATLAB and depicts the trajectory of the finger tips of each finger during the extension and flexion motions of the hand. It can be seen that the motion is a natural one and the model can be used to conceive a basic prosthetic device.

KEYWORDS: human hand constraints, human hand prosthesis, joints, kinematics of hand prosthesis

1 INTRODUCTION

The development of a human hand prosthesis which can be felt as part of the body by the amputees is far to became reality. Actually, the existing prosthetic devices for the upper limb are unable to provide enough grasping functionalities, the main problem being the lack of the degrees of freedom (DoFs) [8]. This problem is generated by the limited space available to integrate actuators within the prosthetic hand. Still, recent progress in sensors, actuators and embedded control technologies are encouraging the development of a new generation of artificial hands [1]. These components can, potentially, provide the solution for obtaining more active joints, since they can be integrated inside the structure of the prosthetic hand. Following this trend, the paper presents the first step of obtaining a better hand prosthesis process, the modeling. The human hand and the fingers represent highly articulated systems submitted to natural anatomical restrictions. To model the fingers joints and links, the kinematic chain of each finger should be represented.

2 KINEMATIC MODEL

Human hand has five fingers, all of them having approximate equal lengths, three phalanges and the same kind of motion, except the thumb able to move in opposition with the other fingers (Figure 1). The kinematic model of the human hand (Figure 2) was realized by considering [3]:

- wrist as a superposition of three independent, orthogonal and simple revolute joints;
- metacarpophalangeal (MCP) joint as a superposition of two independent, orthogonal and simple revolute joints;
- proximal interphalangeal (PIP) joint as simple revolute joint.
- distal interphalangeal (DIP) joint as simple revolute joint;

Based on Denavit-Hartenberg convention [2], the geometrical parameters are obtained (Table 1), which were used to determine the correspondent transfer matrices. One can observe that, in the case of the lateral fingers (meaning pinky, ring and index), the kinematic chain is the same, the only difference being the distances L_x. In Table 1, q_1, q_2, q_{3x}, q_{4x}, q_{5x}, q_{6x}, q_{7x} are joint variables, p is the length of the palm, and f_{1x}, f_{2x}, f_{3x} are the lengths of the finger's phalanges.

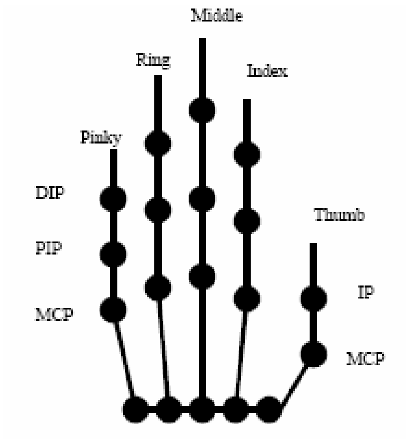


Figure 1. The model of the human hand

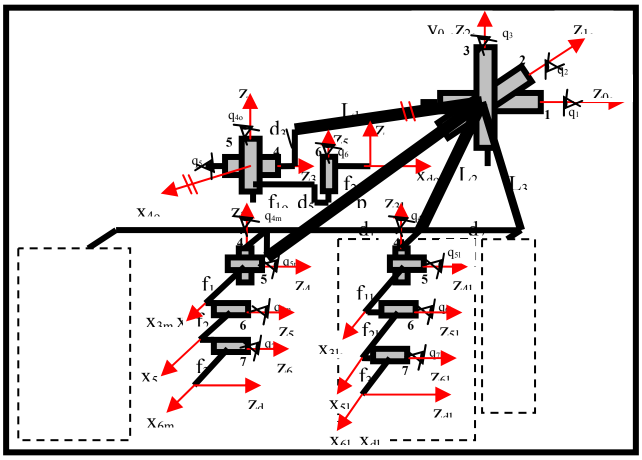


Figure 2. The kinematic model of the human hand

Table 1. The geometric parameters of the hand

No	θ_i	L_i	d_i	α_i	No	θ_i	L_i	d_i	α_i	No	θ_i	L_i	d_i	α_i
1	q_1	0	0	90	1	q_1	0	0	90	1	q_1	0	0	90
2	q_2	0	0	90	2	q_2	0	0	90	2	q_2	0	0	90
3_o	q_{3o}	L_1	d_3	-90										
4_o	q_{4o}	0	0	90										
5_o	q_{5o}	f_{1o}	d_5	0										
6_o	q_{6o}	f_{2o}	0	0										
					3_m	q_{3m}	p	0	0					
					4_m	q_{4m}	0	0	-90					
					5_m	q_{5m}	f_{1m}	0	0					
$d_3, d_5 = negatives$					6_m	q_{6m}	f_{2m}	0	0					
					7_m	q_{7m}	f_{3m}	0	0					
										3_l	q_{3l}	$L_{2,3}$	0	0
										4_l	q_{4l}	0	0	-90
										5_l	q_{5l}	f_{1l}	0	0
										6_l	q_{6l}	f_{2l}	0	0
										7_l	q_{7l}	f_{3l}	0	0

The general transfer matrices (one for each finger) result by multiplying the corresponding transfer matrices. Each column of a general transfer matrix represents one of the kinematic equations describing the corresponding finger motion (axes orientations and origin positions of the reference frame attached to the finger tip) with respect to the general coordinate system, placed on the first revolute joint of the wrist.

For example, for the thumb, the kinematic equations are:

- direction of the unit vector $\vec{n}$

$$n_x = \cos(q_5+q_6)\cdot[\cos(q_1)\cdot\cos(q_2)\cdot\cos(q_3)\cdot\cos(q_4)-\cos(q_1)\cdot\sin(q_2)\cdot\sin(q_4)+\sin(q_1)\cdot\sin(q_3)\cdot\cos(q_4)]+ \\ +\sin(q_5+q_6)\cdot[-\cos(q_1)\cdot\cos(q_2)\cdot\sin(q_3)+\sin(q_1)\cdot\cos(q_3)]$$

$$n_y = \cos(q_5+q_6)\cdot[\sin(q_1)\cdot\cos(q_2)\cdot\cos(q_3)\cdot\cos(q_4)-\sin(q_1)\cdot\sin(q_2)\cdot\sin(q_4)-\cos(q_1)\cdot\sin(q_3)\cdot\cos(q_4)]+ \\ +\sin(q_5+q_6)\cdot[-\sin(q_1)\cdot\cos(q_2)\cdot\sin(q_3)-\cos(q_1)\cdot\cos(q_3)] \tag{1}$$

$$n_z = \cos(q_5+q_6)\cdot[\sin(q_2)\cdot\cos(q_3)\cdot\cos(q_4)+\cos(q_2)\cdot\sin(q_4)]-\sin(q_5+q_6)\cdot\sin(q_2)\cdot\sin(q_3)$$

- direction of the unit vector $\vec{o}$

$$o_x = -\sin(q_5+q_6)\cdot[\cos(q_1)\cdot\cos(q_2)\cdot\cos(q_3)\cdot\cos(q_4)-\cos(q_1)\cdot\sin(q_2)\cdot\sin(q_4)+\sin(q_1)\cdot\sin(q_3)\cdot\cos(q_4)]+ \\ +\cos(q_5+q_6)\cdot[-\cos(q_1)\cdot\cos(q_2)\cdot\sin(q_3)+\sin(q_1)\cdot\cos(q_3)]$$

$$o_y = -\sin(q_5+q_6)\cdot[\sin(q_1)\cdot\cos(q_2)\cdot\cos(q_3)\cdot\cos(q_4)-\sin(q_1)\cdot\sin(q_2)\cdot\sin(q_4)-\cos(q_1)\cdot\sin(q_3)\cdot\cos(q_4)]+ \\ +\cos(q_5+q_6)\cdot[-\sin(q_1)\cdot\cos(q_2)\cdot\sin(q_3)-\cos(q_1)\cdot\cos(q_3)] \quad (2)$$

$$o_z = -\sin(q_5+q_6)\cdot[\sin(q_2)\cdot\cos(q_3)\cdot\cos(q_4)+\cos(q_2)\cdot\sin(q_4)]-\sin(q_5+q_6)\cdot\sin(q_2)\cdot\sin(q_3)$$

- direction of the unit vector $\vec{a}$

$$a_x = \cos(q_4)\cdot\cos(q_1)\cdot\sin(q_2)+\sin(q_4)\cdot[\cos(q_1)\cdot\cos(q_2)\cdot\cos(q_3)+\sin(q_1)\cdot\sin(q_3)]$$

$$a_y = \cos(q_4)\cdot\sin(q_1)\cdot\sin(q_2)+\sin(q_4)\cdot[\sin(q_1)\cdot\cos(q_2)\cdot\cos(q_3)-\cos(q_1)\cdot\sin(q_3)] \quad (3)$$

$$a_z = -\cos(q_2)\cdot\cos(q_4)+\sin(q_2)\cdot\cos(q_3)\sin(q_4)$$

- position vector $\vec{p}$ of the reference frame origin

$$p_x = [f_{2o}\cdot\cos(q_5+q_6)+f_{1o}\cdot\cos(q_5)]\cdot(\cos(q_1)\cdot\cos(q_2)\cdot\cos(q_3)\cdot\cos(q_4)-\cos(q_1)\cdot\sin(q_2)\cdot\sin(q_4)+\sin(q_1)\cdot\sin(q_3)\cdot\cos(q_4))+ \\ +\left(\frac{p}{2}-d_5\cdot\sin(q_4)\right)\cdot[\cos(q_1)\cdot\cos(q_2)\cdot\cos(q_3)+\sin(q_1)\cdot\sin(q_3)]-(d_5\cdot\cos(q_4)+d_3)\cdot\cos(q_1)\cdot\sin(q_2)+ \\ +[f_{2o}\cdot\sin(q_5+q_6)+f_{1o}\cdot\sin(q_5)-d_1-d_2](-\cos(q_1)\cdot\cos(q_2)\cdot\sin(q_3)+\sin(q_1)\cdot\cos(q_3))$$

$$p_y = [f_{2o}\cdot\cos(q_5+q_6)+f_{1o}\cdot\cos(q_5)]\cdot(\sin(q_1)\cdot\cos(q_2)\cdot\cos(q_3)\cdot\cos(q_4)-\sin(q_1)\cdot\sin(q_2)\cdot\sin(q_4)-\cos(q_1)\cdot\sin(q_3)\cdot\cos(q_4))+ \\ +\left(\frac{p}{2}-d_5\cdot\sin(q_4)\right)\cdot[\sin(q_1)\cdot\cos(q_2)\cdot\cos(q_3)-\cos(q_1)\cdot\sin(q_3)]-(d_5\cdot\cos(q_4)+d_3)\cdot\sin(q_1)\cdot\sin(q_2)- \\ -[f_{2o}\cdot\sin(q_5+q_6)+f_{1o}\cdot\sin(q_5)-d_1-d_2](\sin(q_1)\cdot\cos(q_2)\cdot\sin(q_3)+\cos(q_1)\cdot\cos(q_3)) \quad (4)$$

$$p_z = [f_{2o}\cdot\cos(q_5+q_6)+f_{1o}\cdot\cos(q_5)]\cdot(\sin(q_2)\cdot\cos(q_3)\cdot\cos(q_4)+\cos(q_2)\cdot\sin(q_4))+\left(\frac{p}{2}-d_5\cdot\sin(q_4)\right)\cdot\sin(q_2)\cdot\cos(q_3)+ \\ +(d_5\cdot\cos(q_4)+d_3)\cdot\cos(q_2)-[f_{2o}\cdot\sin(q_5+q_6)+f_{1o}\cdot\sin(q_5)-d_1-d_2]\sin(q_2)\cdot\sin(q_3)$$

3 THE CONSTRAINTS OF THE HUMAN HAND

Assembly palm&fingers model motion is constrained because the real hand cannot make arbitrary gestures. Hand constraints can be divided into three types [6]:

- type I constraints are the limits of finger motions as a result of hand anatomy (static constraints):

$$-90°\le q_1\le 90° \qquad -15°\le q_2\le 15°$$
$$-15°\le q_3\le 15° \qquad -15°\le q_{4x}\le 15° \qquad (5)$$
$$0°\le q_{5x}\le 90° \qquad 0°\le q_{6x}\le 110°$$
$$0°\le q_{7x}\le 90°$$

- type II constraints are the limits imposed on joints during motion (dynamic constraints) [5]:

$$q_{DIP}=\frac{2}{3}q_{PIP} \quad (6)$$

- type III constraints, which are applied in performing natural motion (more subtle to detect and difficult to express in a mathematical form).

4 MOTION STUDY USING MATLAB

The paper presents the study of the extension and flexion motions of the hand, respecting the constraints of the natural model and the following considerations: the wrist is rigid, all central fingers have no adduction/abduction motion (meaning $q_1=q_2=q_3=q_4=0$) and the thumb moves only the last phalange (to simplify the model).

To realize the hand model, one has to describe the kinematic chains for each finger, with respect to a general coordinate system (CS), placed on the wrist. The general transfer matrix of each finger expresses the orientation and the position of the corresponding fingertip. Covering the possible range of each movable joint variable one can determine the fingertip's trajectory with respect to the general coordinate system.

To express the position of each fingertip, the corresponding kinematic equation (the position and orientation of the thumb's fingertip are stated by the (1)–(4) equations) were translated into MATLAB functions. There are some considerations regarding the fingers' position and motion with respect to the general CS:

- The middle finger is placed along the Ox axis, with the origin of the proximal phalange at a distance *p* from the origin of the CS (the length of the palm), and moves around Oz axis towards Oy axis;
- The ring finger is parallel with the middle finger, placed to a distance d_1 on Oz axis, and has the same motion;
- The pinky finger is parallel with the ring finger, placed to a distance d2 from it on Oz axis, and has the same motion;
- The index finger is parallel with the middle finger, placed to a distance $-d_1$ from it on Oz axis, and has the same motion;
- The thumb is placed at *p/2* from the origin on Ox axis, has the origin of the first phalange situated at $-d_3$ on Oy axis and the origin of the second phalange at $-d_5$ on Oy axis, and moves around Oy axis.

In order to generate the motions' curves, one has to set all the necessary dimensions:

- General dimensions:

$$
\begin{aligned}
p &= 10\ cm = 0{,}1\ m \\
d_1 &= 3\ cm = 0{,}03\ m \\
d_2 &= 2\ cm = 0{,}02\ m \\
d_3 &= 2\ cm = 0{,}02\ m \\
d_5 &= 3\ cm = 0{,}03\ m
\end{aligned} \tag{7}
$$

- Thumb

$$
\begin{aligned}
f_{1o} &= 3{,}5\ cm = 0{,}035\ m \\
f_{2o} &= 2{,}5\ cm = 0{,}025\ m
\end{aligned} \tag{8}
$$

- Index

$$
\begin{aligned}
f_{1a} &= 4{,}5\ cm = 0{,}045\ m \\
f_{2a} &= 3\ cm = 0{,}03\ m \\
f_{3a} &= 2\ cm = 0{,}02\ m
\end{aligned} \tag{9}
$$

- Middle

$$
\begin{aligned}
f_{1m} &= 5\ cm = 0{,}05\ m \\
f_{2m} &= 3{,}5\ cm = 0{,}035\ m \\
f_{3m} &= 2{,}5\ cm = 0{,}025\ m
\end{aligned} \tag{10}
$$

- Ring

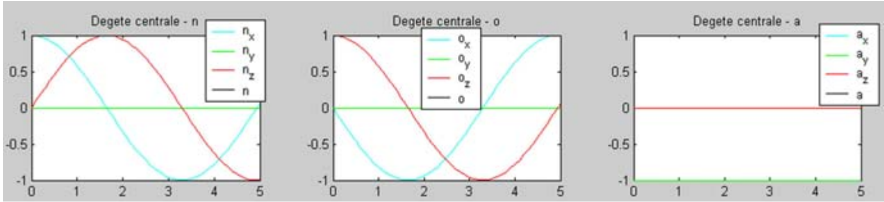
$$
\begin{aligned}
f_{1i} &= 5\ cm = 0{,}05\ m \\
f_{2i} &= 3{,}5\ cm = 0{,}035\ m \\
f_{3i} &= 2\ cm = 0{,}02\ m
\end{aligned} \tag{11}
$$

- Pinky

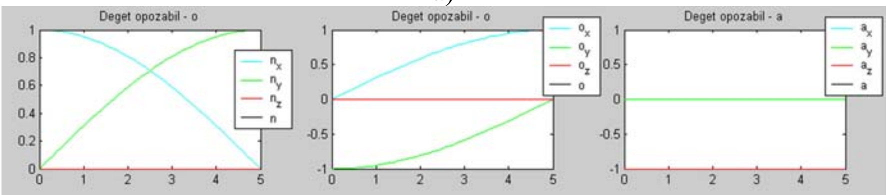
$$
\begin{aligned}
f_{1c} &= 4\ cm = 0{,}04\ m \\
f_{2c} &= 2{,}5\ cm = 0{,}025\ m \\
f_{3c} &= 2\ cm = 0{,}02\ m
\end{aligned} \tag{12}
$$

The motion is studied on a time slot of 5s, divided in slices with a step $s = 0.1$. For each slice, the current position of the fingertip is calculated using the corresponding values of the joint variables.

To perform the flexion motion, the movable joint variables start from the lowest possible value (full extension) and increase until the highest possible value is reached (full flexion), when the motion stops. To extend the fingers, the movable joint variables start from the highest possible value (full flexion) and increase until the lowest possible value is reached (full extension), when the motion stops. The orientation of the coordinate systems attached to the fingertips, and the fingertips trajectories for each finger are presented in Figure 3 and 4 for flexion motion, and in Figure 5 and 6 for extension motion.

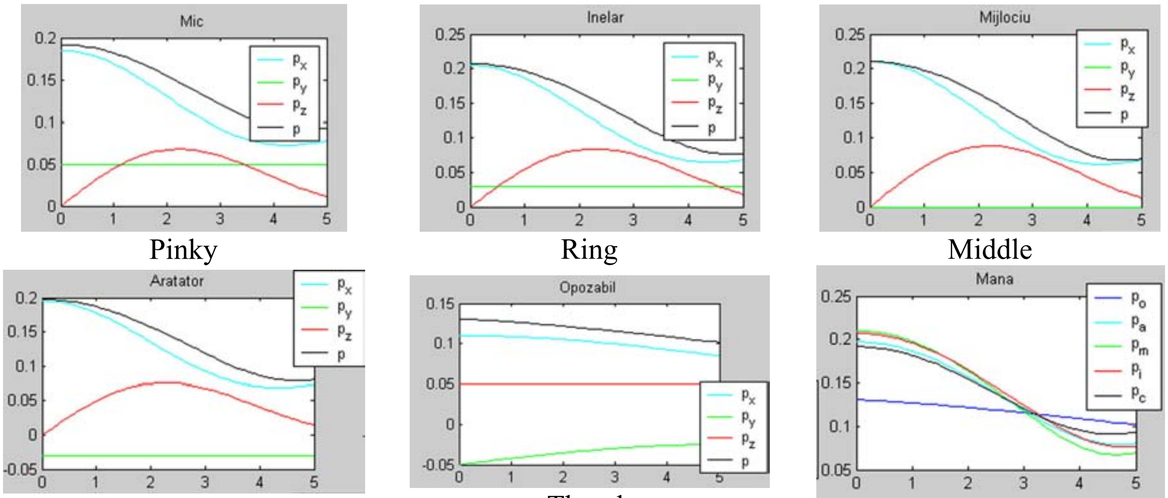


a)



b)

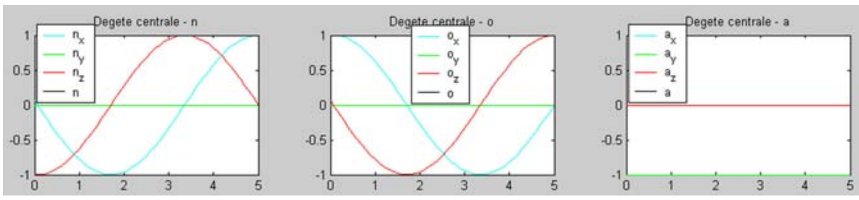
Figure 3. The orientations of the CSs attached to the fingertips of a) central fingers and b) thumb in flexion motion of the hand



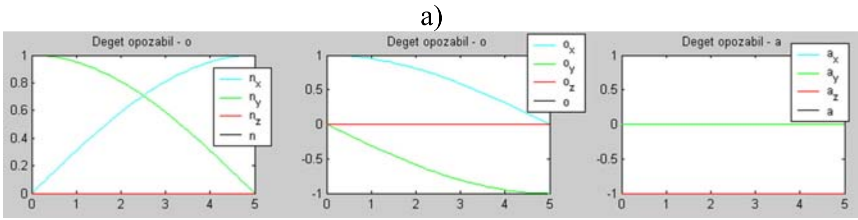
Pinky Ring Middle

Index Thumb Hand

Figure 4. The trajectories of the fingertips in the flexion motion of the hand



a)



b)

Figure 5. The orientations of the CSs attached to the fingertips of a) central fingers and b) thumb in extension motion of the hand

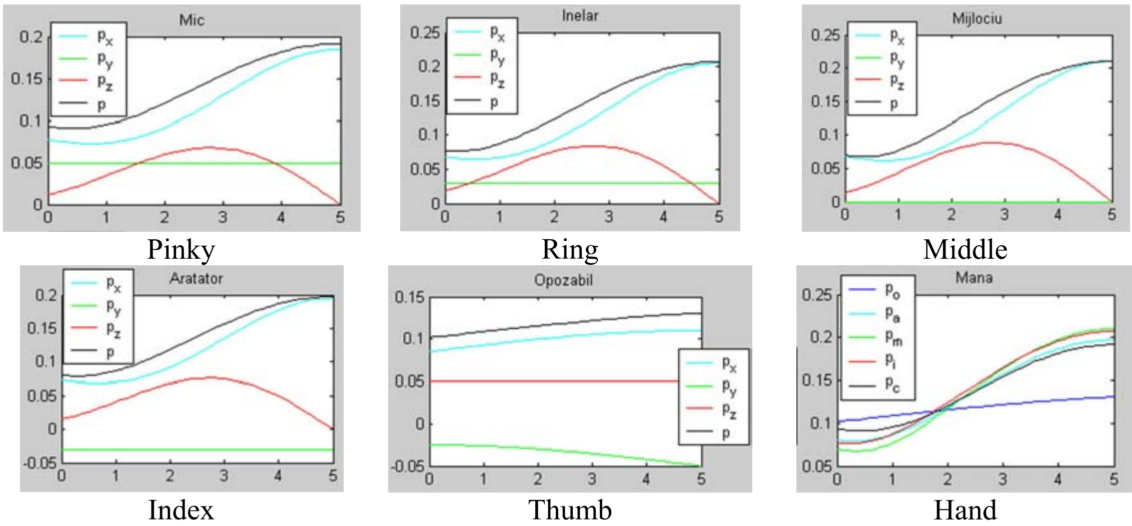


Figure 6. The trajectories of the fingertips in the extension motion of the hand

From the Figures 3–6 one can see that the motion of the model is human like, so the model can be successfully used to implement a human hand prosthesis.

5 CONCLUSIONS

The kinematic study of the human fingers is very useful to conceive a basic prosthetic device because the mass of phalanges is very small and the dynamic model is not necessary. The only problem is to choose the appropriate actuators able to assure the laws of motion described by the kinematic equations and to manufacture the phalanges and the joints, as anatomical as possible, in a light material like Aluminum, Titanium, rigid plastic material, etc.

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