The Dynamic Study of the Palm-Middle Finger System

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Abstract: The dynamic modeling of the human hand is necessary because its normal physiological motions require dynamics. The human hand it is a mechanism having many degrees of freedom, so the system of differential equations obtained modeling the hand it is very complex and imposes a numerical solution. This paper presents a dynamic model of the palm-middle finger system, in which the only approximation is the average density used to generate the mass of the system. The solutions obtained after the simulation in Matlab are very realistic and can be successfully used in the process of selecting the necessary motors to drive a human hand prosthesis

Keywords: dynamics of human hand, human hand prosthesis

1 Introduction

The prosthesis for human hand, which can be used to replace the upper limb, have alot in common with a robot end effector used in industry. Still, a human hand prosthesis design has a set of constraints which is different from the one corresponding to an industrial application, mainly because the prosthesis is highly customized and has to offer serious advantages to the patient in order for he/she to were it.

The development of artificial systems capable to imitate the human body generates fascinating problems regarding its ability of manipulating things. An impressive number of prosthesis for human hand has been developed until present days [2, 5, 6, 10, 11, 12, 13], but none of them can perform as many tasks as the natural model. Despite the huge research done among the World aiming the development of an innovative human hand prosthesis, studies have been shown that a great number of human hand prosthesis users do not currently use their prosthesis (between 30% and 50% [2]). To convince the patients to use such prosthesis, some criteria must be fulfilled [9]: cosmetic appeal, comfort, and control.

The first step in the process of obtaining efficient hand prosthesis and cosmetic appearance for them is the study of the natural model. The human hand consists of connected parts composing kinematical chains so that hand motion is highly articulated (Figure 1). 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 [3, 4]. At the same time, many constraints among fingers and joints make the hand motion even harder to model.

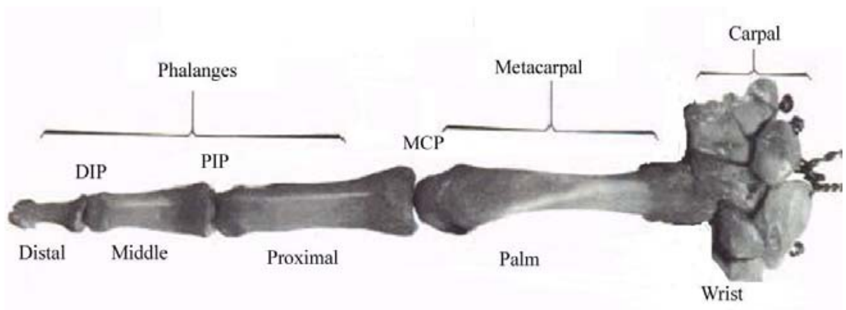

Figure 1
The anatomical model of the proposed system

The dynamic modeling of the human hand is necessary because its normal physiological motions require dynamics. The human hand it is a mechanism having many degrees of freedom (DoFs), so the system of differential equations obtained modeling the hand it is very complex and imposes a numerical solution [4]. Most of the time, the resulting model is a simplified one, especially when modeling the human body where the phenomenons are of such a complexity that an exact mathematical reproduction is, practically, impossible. In order to obtain correct results when solving the differential equations, a study of the biological properties of the materials, which compose the system, and a determination of all the necessary dimensions are required [1, 8].

This paper presents a simplified model, composed by the wrist and the middle finger. The dynamic model of this system is studied in the specific situation of catching an object of a certain weight. The numerical solutions obtained will be very useful to select the proper motors to actuate the system.

2 Method

The kinematical chain of the proposed system contains the palm and the three phalanges of the middle finger: proximal, middle, and distal phalanges (Figure 2). These elements are linked through rotational joints, which allow the general motion of the system. The wrist has three DoFs (three rotational couples, the general coordinated system being placed on the first of them), the metacarpophalangeal joint has two DoFs (adduction/abduction and flexion/extension), and the proximal interphalangeal and distal interphalangeal joints have one DoF each (flexion/extension). Each joint motion it is expressed using a joint variable, from q_1, for the first rotational couple, to q_7, the last rotational couple. To determine the final form of the differential equations, the dimensions of an adult human hand were considered. In this case, for the dynamic study, the Lagrange equations were used, under the form (1.1).

$$\frac{d}{dt}\left(\frac{\partial E_c}{\partial \dot{q}_i}\right)-\frac{\partial E_c}{\partial q_i}=Q_i \tag{1}$$

where Q_i are the generalized forces.

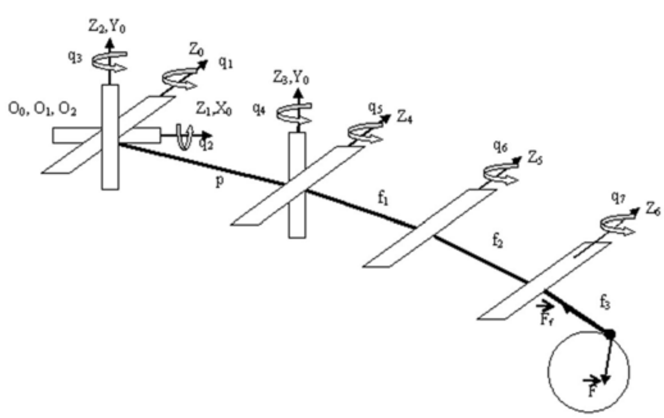

Figure 2
The kinematical model of the proposed system

The first thing to do is to calculate de kinetic energy of the system, which is the sum of the kinetic energies of the composing elements. Because there are only rotational joints, the kinetic energies are:

$$E_{c1}=\frac{1}{2}\left(J_{z0}^{(1)}\cdot\dot{q}_1^{\,2}+J_{z1}^{(1)}\cdot\dot{q}_2^{\,2}+J_{z2}^{(1)}\cdot\dot{q}_3^{\,2}\right)$$

$$E_{c2}=\frac{1}{2}\left(J_{z0}^{(2)}\cdot\dot{q}_1^{\,2}+J_{z1}^{(2)}\cdot\dot{q}_2^{\,2}+J_{z2}^{(2)}\cdot\dot{q}_3^{\,2}+J_{z3}^{(2)}\cdot\dot{q}_4^{\,2}+J_{z4}^{(2)}\cdot\dot{q}_5^{\,2}\right) \tag{2}$$

$$E_{c3}=\frac{1}{2}\left(J_{z0}^{(3)}\cdot\dot{q}_1^{\,2}+J_{z1}^{(3)}\cdot\dot{q}_2^{\,2}+J_{z2}^{(3)}\cdot\dot{q}_3^{\,2}+J_{z3}^{(3)}\cdot\dot{q}_4^{\,2}+J_{z4}^{(3)}\cdot\dot{q}_5^{\,2}+J_{z5}^{(3)}\cdot\dot{q}_6^{\,2}\right)$$

$$E_{c4}=\frac{1}{2}\left(J_{z0}^{(4)}\cdot\dot{q}_1^{\,2}+J_{z1}^{(4)}\cdot\dot{q}_2^{\,2}+J_{z2}^{(4)}\cdot\dot{q}_3^{\,2}+J_{z3}^{(4)}\cdot\dot{q}_4^{\,2}+J_{z4}^{(4)}\cdot\dot{q}_5^{\,2}+J_{z5}^{(4)}\cdot\dot{q}_6^{\,2}+J_{z6}^{(4)}\cdot\dot{q}_7^{\,2}\right)$$

Using Solid Works, one can determine, for the proposed system, the axial moments of inertia for each element, with respect to the own coordinate system and to the own center of mass. Prior to this, the model has to be built in Solid Works, respecting all the motion constraints and all the dimensions of the natural model. In order to achieve this, the Mass Property tool of Solid Works was used. Although the human bones don't have a homogenous structure, the mass was calculated for an average density of $\rho = 1{,}3 \quad g/cm^3$.

To determine the moments of inertia with respect to the necessary axes, other than the own axes, the Steiner formula has been used (Equation (3) presents the way that the axial moment of inertia $J_{z0}^{(2)}$ is calculated).

$$J_{z0}^{(2)}=J_{\|z0C2}^{(2)}+d_{21}^{2}\cdot m_{fp} \tag{3}$$

The distances which appear describe the influence of the joint variables prior to the current one over this current joint. These values can be calculated using the last column of the general matrix which expresses the translation from the mass center of the current element to the necessary joint, respecting the low of variation of the axial moments of inertia (Equation (4)).

$$J_{z1}=J_z+(x_{1C}^2+y_{1C}^2)\cdot M \tag{4}$$

For exemple, to calculate the axial moment of inertia of the proximal phalange with respect to the three axes of rotation situated on the wrist, the necessary projections are:

$$p_{x2}=c1c2\left(\frac{f_1}{2}c34c5+pc3\right)-\frac{f_1}{2}c1s2s5+s1\left(\frac{f_1}{2}s34c5+ps3\right)$$

$$p_{y2}=s1c2\left(\frac{f_1}{2}c34c5+pc3\right)-\frac{f_1}{2}s1s2s5-c1\left(\frac{f_1}{2}s34c5+ps3\right) \tag{5}$$

$$p_{z2}=s2\left(\frac{f_1}{2}c34c5+pc3\right)+\frac{f_1}{2}c2s5$$

where $ci = cos\ q_i$ and $si = sin\ q_i$.

The resulting form of the kinetic energy is:

$$
\begin{aligned}
E_{c1} = \frac{1}{2}\Big[& \dot{q}_1^{\,2} \cdot \Big(J_{z0}^{(1)} + J_{\|z0C2}^{(2)} + m_{fp} \cdot \left(p_{x2}^2 + p_{y2}^2\right) + J_{\|z0C3}^{(3)} + m_{fm} \cdot \left(p_{x3}^2 + p_{y3}^2\right) + J_{\|z0C4}^{(4)} + m_{fd} \cdot \left(p_{x5}^2 + p_{y5}^2\right)\Big) + \\
& + \dot{q}_2^{\,2} \cdot \Big(J_{z1}^{(1)} + J_{\|z1C2}^{(2)} + m_{fp} \cdot \left(p_{y2}^2 + p_{z2}^2\right) + J_{\|z1C3}^{(3)} + m_{fm} \cdot \left(p_{y3}^2 + p_{z3}^2\right) + J_{\|z1C4}^{(4)} + m_{fd} \cdot \left(p_{y5}^2 + p_{z5}^2\right)\Big) + \\
& + \dot{q}_3^{\,2} \cdot \Big(J_{z2}^{(1)} + J_{\|z2C2}^{(2)} + m_{fp} \left(p_{x2}^2 + p_{z2}^2\right) + J_{\|z2C3}^{(3)} + m_{fm} \cdot \left(p_{x3}^2 + p_{z3}^2\right) + J_{\|z2C4}^{(4)} + m_{fd} \cdot \left(p_{x5}^2 + p_{z5}^2\right)\Big) + \\
& + \dot{q}_4^{\,2} \cdot \Big(J_{z3}^{(2)} + J_{\|z3C3}^{(3)} + m_{fm} \cdot \left(p_{x4}^2 + p_{y4}^2\right) + J_{\|z3C4}^{(4)} + m_{fd} \cdot \left(p_{x6}^2 + p_{y6}^2\right)\Big) + \\
& + \dot{q}_5^{\,2} \cdot \Big(J_{z4}^{(2)} + J_{\|z4C3}^{(3)} + m_{fm} \cdot \left(p_{x4}^2 + p_{z4}^2\right) + J_{\|z4C4}^{(4)} + m_{fd} \cdot \left(p_{x6}^2 + p_{z6}^2\right)\Big) + \\
& + \dot{q}_6^{\,2} \cdot \Big(J_{5}^{(3)} + J_{\|z5C4}^{(4)} + m_{fd} \cdot \left(p_{x7}^2 + p_{y7}^2\right)\Big) + \\
& + \dot{q}_7^{\,2} \cdot J_{z6}^{(4)} \Big]
\end{aligned}
\tag{6}
$$

To determine the general form of the left side in the resulting Langrange equations, one have to calculate the partial derivatives of the Lagrangian with respect to $\dot{q}_i$ and q_i, and the derivatives with respect to time of the first partial derivatives. Having in mind that the expressions of the moments of inertia relies on the above mentioned distances (which depend also on the joint variable q_i) in the first step one have to determine the derivatives of these distances.

In the right side of the Lagrange equations there are the generalized forces which have the form (7):

$$Q = [M_1 \quad M_2 \quad M_3 \quad M_4 \quad M_5 \quad M_6 \quad M_7] \tag{7}$$

In order to calculate the generalized forces, one has to determine the torque in joints by reducing the torque which appears in the finger tip when holding an object. Assuming that the object to be held has 1 g, the torque in the finger tip has the form (8):

$$^{G_7}\tau_{O_7} = \left[-9 \cdot 10^{-3} \quad 10^{-2} \quad 0 \quad 0 \quad 0 \quad 0\right]^T \tag{8}$$

where: 0.009 N is the drag force which appears when handle the object

0.01 N is the force necessary to sustain the object

This torque will be reduced in the system's joints using the relation (9):

$$Q = J^{T\,G_7}\tau_{O_7} \tag{9}$$

where J is the jacobian matrix of the kinematic chain.

Finally, the torque in joints has the expresions (10)-(16):

$$
\begin{aligned}
M_1 = {} & \sin q_2 \cdot \sin(q_3 + q_4) \cdot [-10^{-2} \cdot f_3 + f_2 \cdot (9 \cdot 10^{-3} \cdot \sin q_7 - 10^{-2} \cdot \cos q_7) + \\
& + f_1 \cdot (9 \cdot 10^{-3} \cdot \sin(q_6 + q_7) - 10^{-2} \cdot \cos(q_6 + q_7))] + \\
& + p \cdot [\cos q_2 \cdot \sin q_3 \cdot \cos(q_3 + q_4) \cdot (-9 \cdot 10^{-3} \cdot \cos(q_5 + q_6 + q_7) - 10^{-2} \cdot \sin(q_5 + q_6 + q_7)) + \\
& + \cos q_3 \cdot \sin(q_3 + q_4) \cdot (9 \cdot 10^{-3} \cdot \cos(q_5 + q_6 + q_7) + 10^{-2} \cdot \sin(q_5 + q_6 + q_7)) - \\
& - \sin q_2 \cdot \sin q_3 \cdot (9 \cdot 10^{-3} \cdot \sin(q_5 + q_6 + q_7) - 10^{-2} \cdot \cos(q_5 + q_6 + q_7))]
\end{aligned} \tag{10}
$$

$$
\begin{aligned}
M_2 = {} & \cos(q_3 + q_4) \cdot [10^{-2} \cdot f_3 + f_2 \cdot (-9 \cdot 10^{-3} \cdot \sin q_7 + 10^{-2} \cdot \cos q_7) + \\
& + f_1 \cdot (-9 \cdot 10^{-3} \cdot \sin(q_6 + q_7) + 10^{-2} \cdot \cos(q_6 + q_7))] + \\
& + p \cdot \cos q_3 \cdot (-9 \cdot 10^{-3} \cdot \sin(q_5 + q_6 + q_7) + 10^{-2} \cdot \cos(q_5 + q_6 + q_7))
\end{aligned} \tag{11}
$$

$$M_3 = 0 \tag{12}$$

$$M_4 = 0 \tag{13}$$

$$M_5 = 10^{-2} \cdot f_3 + f_2 \cdot [-9 \cdot 10^{-3} \cdot \sin q_7 + 10^{-2} \cdot \cos q_7] + f_1 \cdot [-9 \cdot 10^{-3} \cdot \sin(q_6 + q_7) + 10^{-2} \cdot \cos(q_6 + q_7)] \tag{14}$$

$$M_6 = 10^{-2} \cdot f_3 + f_2 \cdot [-9 \cdot 10^{-3} \cdot \sin q_7 + 10^{-2} \cdot \cos q_7] \tag{15}$$

$$M_7 = 10^{-2} \cdot f_3 \tag{16}$$

The seven equations obtained have a very complex form, so a specific tool was used to generate the solutions: Matlab. The expressions of the distances, their derivatives, and the expressions of the equations were translated in Matlab code. At the end of the simulation, the expressions of the joint variables q_i are obtained (Figure 3).

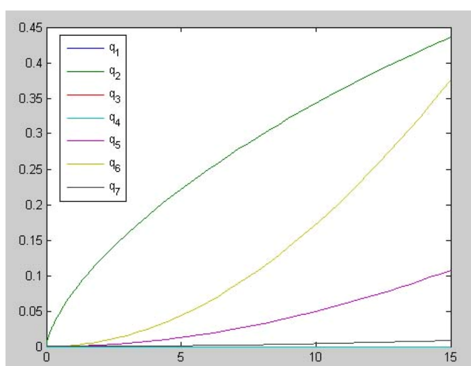

Figure 3
The solutions

Conclusions

This paper presents a dynamic study of the palm middle finger system when holding an object of 1 g. The dynamic model was generated using the Lagrange equations in the general form. To obtain the values for the necessary moments of inertia, a special tool from Solid Works was used. The only approximation for the model is the average density used to generate de mass of the system. The solutions obtained after the simulation in Matlab are very realistic and can be successfully used in the process of selecting the necessary motors to drive a human hand prosthesis.

References

[1] P. Brinckmann, W. Frobin, G. Leivseth: Musculoskeletal biomechanics, in G. Thieme Verlag, Germany, 2002, pp. 155-165

[2] P. Dario, M. C. Carrozza, A. Menciassi, S. Micera, M. Zecca: On the Development of a Cybernetic Hand Prosthesis, in Third IARP International Workshop on Humanoid and Human Friendly Robotics, IARP2002, Tsukuba, Japan, Dec 11-12, 2002

[3] D. Drăgulescu, L. Ungureanu: Human Hand Modeling, in 2nd International Symposium of Theoretical and Applied Mechanics "Dimitrie Mangeron", Iaşi, October 28-30, 2005

[4] D. Drăgulescu, L. Ungureanu: Dynamics of the palm-middle finger system being under the exclusive action of the gravity forces, in Proceeding of RoMedInf, 6-8 April, 2006, pp. 203-206

[5] El Koura, G., Singh, K., Handrix: Animating the Human Hand, in Eurographics/SIGGRAPH Symposium on Computer Animation, 2003

[6] J. J. Kuch, T. S. Huang: Human Computer Interaction via the Human Hand: A Hand Model, in Asilomar Conference on Signals, Systems, and Computers, pp. 1252-1256, 1995

[7] S. Schulz, C. Pylatiuk, G. Bretthauer: A New Ultralight Anthropomorphic Hand, in Proceedings of the 2001 IEEE International Conference on Robotics & Automation, Seul, Korea, May 2001

[8] F. J. Valero-Cuevas: Applying principles of robotics to understand the biomechanics, neuromuscular control and clinical rehabilitation of human digits, in Proceedings of the 2000 IEEE International Conference on Robotics&Automation, San-Francisco, USA, pp. 270-275

[9] H. Visser, J. Herder: Force Directed Design of a Voluntary Closing Hand Prosthesis, in Journal of Rehabilitation Research & Development, Vol. 37, No. 3, pp. 261-272, May/June 2000

[10] J. Yang, E. P. Pitarch, K. Abdel-Malek, A. Patrik, L. Lindkvist: A multi-fingered hand prosthesis, in Mechanism and Machine Theory, No. 39, 2004, pp. 555-581

[11] *** Robonaut, http://robonaut.jsc.nasa.gov/robonaut.html

[12] *** Barrett Hand, http://sbir.gsfc.nasa.gov/SBIR/successes/ss/9-056text.html

[13] *** Dextrous Robot Hands, Institute of Robotics and Mechatronics, http://www.dlr.de/rm/en/Desktopdefault.aspx/