Actuating a Human Hand Prosthesis: Model Study

LOREDANA UNGUREANU[1)], ANTONIUS STANCIU[2)], KAROLY MENYHARDT[3)]
[1)]Automation and Applied Informatics Department, [2)]Computer Science and Engineering Department, [3)]Mechanics and Vibrations Department
"Politehnica" University of Timisoara
Timisoara, 2, Vasile Parvan Blvd., 300223
ROMANIA

Abstract: The researchers all over the world give a lot of attention to modeling the human hand in order to obtain good hand prosthesis. Despite many attempts, very few solutions are available on the market, and even those are far too expensive to reach for most of the patients. Knowing that it is very important to have a model as close as possible to the natural one, we determined the kinematical and dynamical models of the human hand. We realized, also, that if we limit our model's capabilities to the most important function of the hand, namely prehension, considering that the vast majority of potential patients have one good hand for delicate actions, then we can much quickly obtain an affordable human hand prosthesis with grabbing capabilities, to help impaired people to manage through most of the daily activities.

Key-Words: **human hand prosthesis, dynamics of human hand, human hand constraints, automatic system, hand control, kinematics of hand prosthesis**

1 Introduction

The human hand is a very good example of how to implement a complex system capable to fulfill various tasks using a combination of mechanisms, sensors and control functions. There are quite few solutions for human hand prostheses, based on mechanical [5], [15], electrical [1], [16], electromechanical [13], pneumatic [6], [17] or hydraulic [7], [9] implementations, some of them reaching already to the market. By studying the recent achievements in this field, one can observe that there is a trend to increase the dexterity of the prosthesis for the human hand. In the same time, it is also desirable to create simpler, more practical and applicable devices. The models proposed so far (LMS Mechanical Hand of Laboratoire de Mecanique des Solides from Poitiers University [5], Robonaut Hand by Nasa [15], DLR Hand by German Aerospace Center[1], Barrett Hand by Barrett Technology Inc. [16], Shadows Dexterous Hand by Shadow Robot Company [17], Ultralight Hand [9] by Karlsruhe University) represent acceptable solutions, but most of them are too complex to be afforded by the majority of patients (especially the Romanian ones), and difficult to control. Also, none of them can perform as many tasks as the natural model, mostly due to the lack of degrees of freedom (DoF) [12], [14].

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 [2]. Potentially, these components can provide the solution for obtaining more active joints, since they can be integrated inside the structure of the prosthetic hand.

Despite the huge research worldwide, aiming 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% [3]). To convince the patients to use such prostheses, some criteria must be fulfilled [12]: cosmetic appeal, comfort, and control.

In order to obtain a good cosmetic appearance for the prosthesis, it is desirable to design a hand as anatomically as possible. Following this trend, the paper presents a model of the palm and fingers (based on the anatomical one), studies its kinematics and dynamics, and offers a hydraulically based design solution. There are already some solutions based on hydraulic actuation and we consider Ultralight Hand made by Karlsruhe University [9] the most representative one. The authors used flexible fluidic actuators integrated in the joints of the fingers to flex them and spring elements to extend them. We designed a different type of hydraulic actuation for flexing the fingers, having in mind to obtain a better linearity between the variation of the force exerted by the fingers and the actuating force (represented by the pressure of the hydraulic fluid.) The extension of the hand will be made by using repellent springs.

2 Kinematics of the Model

The first step in the process of obtaining efficient hand prosthesis is the study of the natural model. The human hand is highly articulated and to model the articulation of fingers the kinematic model has to be done. This model consists of chains containing bodies connected through joints (Fig. 1). The first body is the palm and links together the wrist and the proximal phalange of each finger, which is the second body of each kinematic chain. The wrist allows the rotation of the hand with respect to the arm, meaning three degree of freedom for the system.

Each of the four central fingers has four DoFs. The metacarpophalangeal (MCP) joint allows two kind of motions (two DoFs) to the proximal phalange of a finger: adduction or abduction (in the palm plane), and flexion and extension (with respect to the palm). The proximal interphalangeal (PIP) joint connects the proximal and medial phalanges and has one DoF. The distal interphalangeal (DIP) joint connects the medial and distal phalanges and has, also, only one DoF.

The thumb has a different structure and has four DoFs, one for the interphalangeal (IP) joint, one for MCP joint and two for trapeziometacarpal (TM) joint, both due to flexion and abduction motions. The thumb is, also, able to move in opposition with other fingers. So, the whole system has a total of 23 DoFs.

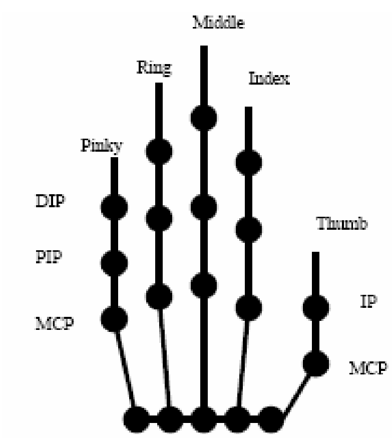

Fig. 1 The model of the human hand

The hand can not make arbitrary gestures, because the motion is submitted to some constraints. Each joint is characterized by a specific geometry and by a minimum and maximum angle. Also, another constraint is introduced by the nature of the hand. For example, to flex or to extend the finger, all the phalanges are moving in the same time and to catch an object each phalange is moving separately [8].

Based on these considerations, we determined the kinematical model of the human hand [10]. Still, we made some approximations, considering the thumb having only two phalanges and establishing its position in the model in such a way that it could move in opposition with the rest of the fingers. Having the motion's equations and knowing the variations of joints' angles, we were able to accurately determine the position of the fingertips. Another constraint consists in the fact that our main objective is the study of the hand's prehension function. So, we created in *SimMechanics*, a tool of *Simulink*, a model to fulfill this goal and we eliminated all the DoFs which are not important for the motion (meaning the DoFs due to the abduction or adduction motion) [4]. This way, the model executes the extension (Fig. 2) and flexion motions, the only ones important for the study. It can be seen (Fig. 2) that the motion is similar to the natural one, so the model can be used to implement the prosthesis.

3 The Dynamic Study of the Model

The dynamic modeling of the human hand is necessary because its normal physiological motions require dynamics. The human hand is a mechanism having many degrees of freedom, so the obtained system of differential equations, modeling the hand, is very complex and imposes a numerical solution [11]. Most of the time, the resulting model is a simplified one, especially when modeling the human body, where the phenomena are of such 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 composing the system and a determination of all the necessary dimensions are required.

For the dynamic study, the Lagrange equations were used, under the form (1):

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

where Q_i are the generalized forces.

In the first step, the kinetic energy of the system has to be calculated, which is the sum of the kinetic energies of the composing elements. Because there are only rotational joints, the kinetic energies are computed using equation (2), where q_i is the corresponding joint variable and J_z is the moment of inertia with respect to the rotational axis.

$$E_{ci} = \frac{1}{2} J_z \dot{q}_i^2 \tag{2}$$

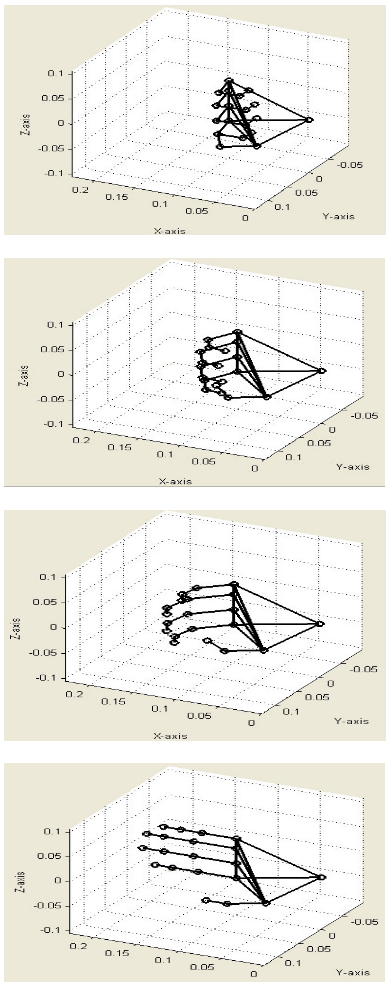

Fig. 2 Extension motion of the model

Having in mind that the general coordinate system is situated on the wrist and the motion is expressed with respect to it, every phalange will have a moment of inertia with respect to the own coordinate system, the own center of mass and the coordinate systems placed between it and the general coordinate system.

Using the *Mass Property* tool of Solid Works, one can determine, for the proposed system (Fig. 3), the axial moments of inertia for each element, with respect to the own coordinate system and to the own center of mass. To determine the moments of inertia with respect to the necessary axes, other than the own, the Steiner formula has been used (equation (3)), where the mentioned distances describe the influence of the joint variables prior to the current one over the 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 axial moments of inertia variation law.

$$J_{z1} = J_z + (x_{1C}^2 + y_{1C}^2) \cdot M \tag{3}$$

Fig. 3 The model of the hand

To determine the general form of the left side in the resulting Lagrange equations, one have to calculate the partial derivatives of the Lagrangean with respect to $\dot{q}_i$ and q_i, and the derivatives with respect to time of the first partial derivatives.

In the right side of the Lagrange equations there are the generalized forces which have the form (4) for each kinematical chain composing the system:

$$Q = [M_1 \quad M_2 \quad M_3 \quad M_4 \quad M_5 \quad M_6 \quad M_7]^T \tag{4}$$

In order to calculate the generalized forces, one has to determine the torque in joints by reducing the torque which appears in the fingertips, when holding an object. This torque will be reduced in the system's joints using the relation (5):

$$Q = J^T \cdot {}^{G_7}\tau_{O_7} \tag{5}$$

where J is the Jacobean matrix of the kinematical chain.

The resulting dynamic equations have a very complex form [11] and to obtain the solution a specialized tool has to be used: Matlab. For example, the solution for the kinematical chain form by the palm and middle finger grabbing an object of 1 g is presented in Fig. 4.

We used these dynamic equations to choose the most suitable motors necessary to drive the prosthesis. So, we decided that miniature stepper motor seems to be, at this point, the best solution for our model, because of many reasons. It provides high torque even at very low rotational speed, which can allow precision movements of the phalanges, without loosing grasp of the prehended object. When not moving, the stepper motor provides an even higher braking torque, which allows to keeping firmly the grabbed object. That way, there is no danger of dropping the object when the motion of the phalanges stops.

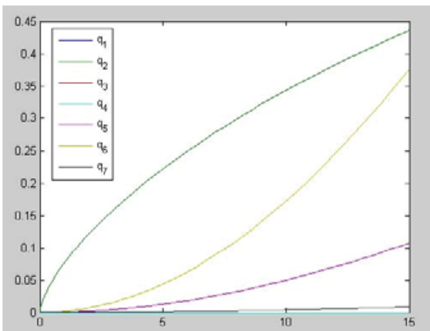

Fig. 4 The solutions for the dynamic equations

4 The Proposed Design Model

It is not yet feasible for us to design, technologically speaking, human hand prosthesis capable to realize all the natural functions. So, we considered that we should focus only on the prehension function, which case it is no longer necessary to know the position of the phalanges at any given time. Studying the way human hand grabs various objects, we observed that the phalanges are closing in, trying to follow the object's contour. Also, when grabbing, the human perception does not focuses on acknowledging every phalange's position, but pays attention to tactile sensations. In this way, dangerous objects are not grabbed and no object is squeeze beyond breaking point. In this case, due to the various natures of the objects to be manipulated, pressure sensors are mandatory.

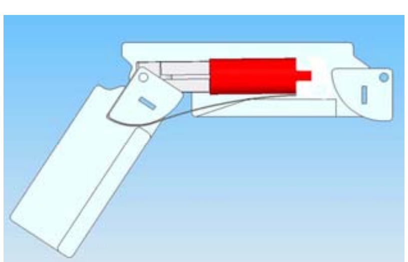

Fig. 5 The articulation between two phalanges

The idea of hydraulic powering of our hand prosthesis originates in the necessity of locating pressure sensor remotely. That way, the forces and torques exerted by the phalanges will be proportional to the pressure of the hydraulic fluid, which will be practically constant (due to negligible quantities and movements of it) in any point of the hydraulic circuit.

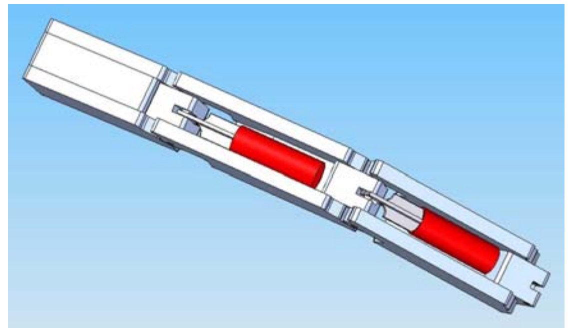

Fig. 6 One finger of the model

When the prosthesis will have to grab an object, the control circuitry will issue to the pumps the command for increasing pressure. A pressure limit will be set for every phalange, according to the nature of the object to be grabbed. Every phalange will start closing in around the object and the movement will stop automatically the moment all the pressure limits were reached. The object is considered grasped and can be moved.

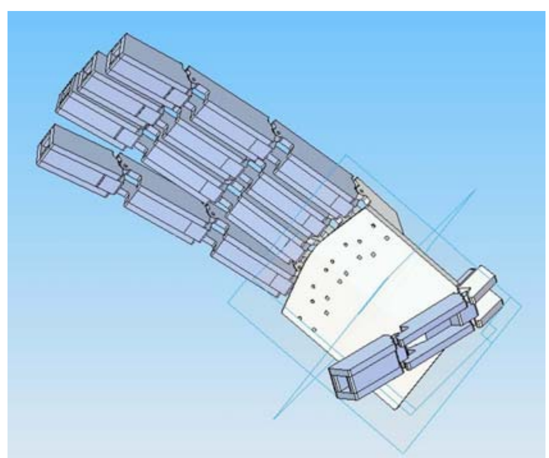

Fig. 7 The proposed model

In order to maintain a linear proportionality between pressure in the hydraulic circuit and the force applied to the phalange, we devise a simple yet effective mechanism, by using a cylindrical sector (Fig. 5) concentric with the articulation of the phalanges and attached to it. When the hydraulic liquid is pushed into the actuator through the nozzle, the increasing pressure will try to push outwards the piston. Because the piston is attached to the hinge between phalanges through a sleeve bearing, only the outer cylinder of the actuator can move, in the opposite direction, in the channel inside the phalange (Fig. 6).

This motion will determine the flexion of the phalange attached to the cylindrical sector, due to the steel belt which connects the outer cylinder of the actuator and the sector. Because the steel belt is not capable of pushing, the extension of the phalanges has to be made using a repellent spring. Fig. 7 presents a general view of the model we propose.

5 Conclusions

The human hand is a fascinating system capable to perform various tasks using a combination of mechanisms, sensors and control functions. In order to obtain a prosthesis which can act as human-like as possible, one have to design a correct model. The kinematic study of the human fingers is very useful to conceive a basic prosthetic device because the mass of phalanges is very small. The only problem is to choose the appropriate actuators able to assure the laws of motion described by the kinematic equations (where the dynamic model has an important role) and to manufacture the phalanges and the joints as anatomically as possible, out of light materials like Aluminum, Titanium, rigid plastics, etc.

We realized that the most important function of the hand for the patients who lost their upper limb is prehension, so our solution restricts, for the moment, the purpose of human hand prosthesis only to this function, intending as future work to implement a fully functional prosthesis. This idea originates from the fact that the vast majority of potential patients have one good hand for delicate actions and one affordable prosthesis with grabbing capabilities (to replace the missing one) will help them to manage through most of the daily activities.

Our proposed model is capable to realize the prehension function for large diversity of objects (of either regular or irregular shape). The pressure in each hydraulic circuit varies linearly proportional to the force exerted by its respective phalange on the grabbed object. Those characteristics make our model one of the simpler, yet reliable and non-expensive, among the specific research in the field.

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