Buletinul Ştiinţific al Universităţii „Politehnica” din Timişoara

Seria ELECTRONICĂ şi TELECOMUNICAŢII
TRANSACTIONS on ELECTRONICS and COMMUNICATIONS

Tom 53(67), Fascicola 1, 2008

The Dynamic Model of an Artificial Hand

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Abstract. The development of artificial systems capable to mimic the human body rise fascinating problems regarding its capability of manipulating things. In order to obtain a human hand prosthesis easy to use, light and cosmetically appealing, one have to study the natural hand and to obtain its kinematical model. Also, 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. These models can be used as a solid base to design satisfactory human hand prostheses. The paper presents a dynamical model of the human hand used to create a hydraulically based design for a human hand prosthesis.

Keywords: dynamic modeling, artificial hand, MATLAB and SimMechanics simulations

I. INTRODUCTION

Even with the technological advances, the human hand is the primary source of dexterous activities. Hand motions are also extensively used in high technology areas such as virtual reality (VR) and tele-operation [12].

The development of artificial systems capable to mimic the human hand raises many problems regarding its capability of manipulating objects. Biomechanical models of the human hand are of great importance in the biomedical and medical ergonomic fields. Different aspects of hand function have been investigated by various researchers and many human hand prostheses have been developed until now worldwide, few of them are already on the market, but are far too expensive to reach for most of the patients, too complex and difficulty to control.

In order to obtain a prosthesis as close as possible to human hand, it was important to study the natural model to offer the user comfort and function ability [1] and to be sure that the patients will actually wear it (statistics shown that, even they posses a hand prosthesis, only between 50% and 70% of the patients currently use the device replacing their hand [11]).

Dynamic effects of hand movements have been considered only very recently. Human hands, being rigid bodies with mass and volume [8], are affected by the forces invoked by motion. Dynamic equations of motion should be considered in rapid hand motions. When the data needed for dynamic analysis, such as joint angle, joint angular velocity, joint angular acceleration, link mass, link length and joint thickness are available through measurement systems, dynamic analysis can be conducted [12].

Artificial hand dynamics deals with the mathematical formulations of the hand’s motion equations. The dynamic equations of a manipulator’s motion are a set of mathematical equations describing the dynamic behavior of the manipulator. Such equations of motion are useful for computer simulation of the robot hand motion, the design of suitable control equations for a robot hand, and the evaluation of the kinematic design and structure of a robot hand [4], [12].

There are few methods to determine the dynamic equations of a robot. The most suitable solution for open chains of connected elements, like human hand, is represented by the Lagrange’s dynamics formulation, together with the Denavit–Hartenberg’s link coordinate representation. This method is preferred in [12] to investigate the characteristics of finger motion. For that the dynamic equations of motion from robot arm dynamics were adopted and modified. Hand anthropometric data such as the mass and length of finger segment, and thickness of joint were measured for eight male subjects. CyberGloveTM was used to measure joint angles of each finger during repetitive flexion and extension. Their results, from the two experiments with repetitive finger flexion and extension, showed that the dynamic characteristics of the finger motion should be included in the consideration of the hand’s loads during manual tasks.

The same Lagrange method was used in [9] to generate a 3D dynamic model of a human finger for estimating the muscular forces involved during free finger movements. They completed the dynamic equations adding some motion constraints and a minimized non-linear objective function. All the necessary simulations where run in MATLAB.

Another method is developed in [5] and [6] where they considered a linear, second-order translational model at the fingertip. They measured applied force and finger tip acceleration, and calculated velocity

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and displacement curves from the acceleration signal. Also, in [5] an extensive study of the impedance of the human fingers was conducted. They began with an investigation of the impedance of the straightened index finger in extension and abduction at the metacarpal-phalangeal (MCP) joint, continued with an investigation of the impedance of a pinch grasp, built on these results to present and validate a model of the human hand in a drum roll on a musical drum, and finished with an implementation of robotic drumming. This paper presents a dynamical model of the human hand used to design the control of an artificial hand hydraulically actuated. To generate the dynamical equations we used the Lagrange method, based on the kinematical model of the hand created according to the Denavit-Hurtenberg's convention. Due to the huge complexity of the equations, we obtained the solution using MATLAB. We run some simulations regarding specific grabbing situations and we demonstrated that the model is capable of grabbing objects having various sizes and shapes using only the fingertips.

II. THE MODEL

In order to design the human hand prosthesis to be manufactured and tested on human beings a model was created by considering the palm as a parallelepiped body and all the phalanges as cylindrical ones. The model has 22 degrees of freedom (DoFs) materialized by the joints coordinates q_i (i=1, … , 22) revolute joints whose motions can reproduce the human hand gestures (Fig. 1 [2]).

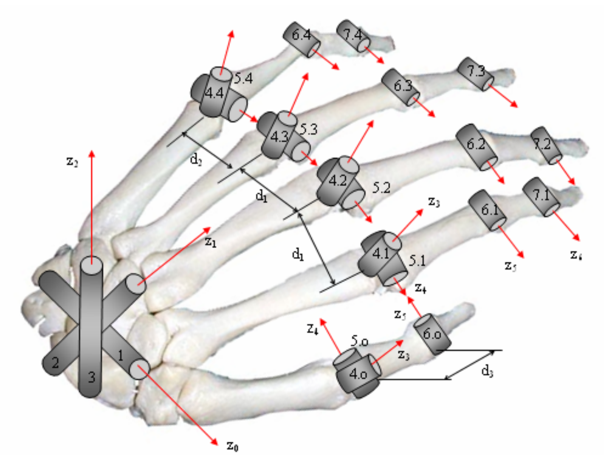

Fig. 1 The kinematical model of the human hand

The hand cannot make arbitrary gestures, because the motion is submitted to motion constraints. Each joint is characterized by a specific geometry and by a minimum and maximum angle between connected bodies. Another constraint is introduced by the nature of the hand. When flexing or extending a finger, all its phalanges are moving in the same time and when catching an object, each phalange moves separately [7].
Having the motion's equations and knowing the variations of joints' angles [7], we were able to accurately determine the position of the fingertips during flexion and extension of the hand. These motions have been considered very important for the main objective of the study, the hand's prehension function.
The dynamic model 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 [10]. In many cases, 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.
We created this dynamic model having in mind to implement an artificial hand and, because to design it from scratch is not a simple task, we decided to create a prosthesis to insure the most important function of the hand, prehension. This function implies grabbing objects of different sizes and shapes. Supposing that the hand will grab an object using only the fingertips (Fig. 2), a torque will appear in every fingertip, which is reduced into system's joints using the equation (1):

$$Q = J^{T\,G_7}\tau_{O_7} \quad (1)$$

where J is the Jacobean matrix of the kinematical chain and Q represents the generalized forces.
The resulting torque in joints will be used to determine the generalized forces, which represent the right side of the Lagrange's equations (2) used to obtain the dynamical model of the system when grabbing an object.

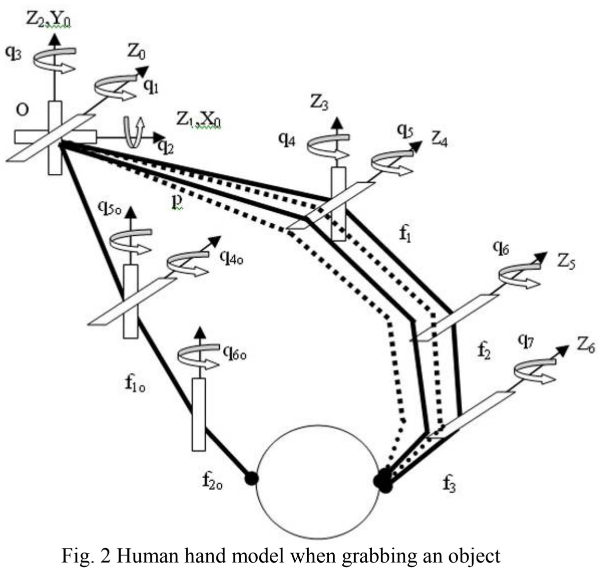

Fig. 2 Human hand model when grabbing an object

$$\frac{d}{dt}\left(\frac{\partial E_c}{\partial \dot{q}_i}\right) - \frac{\partial E_c}{\partial q_i} = Q_i \qquad (2)$$

where E_c is the kinetic energy, q_i represents the joints' coordinates and $\dot{q}_i$ represents the joints' velocity.

To obtain the left side of the Lagrange equations, the kinetic energy of the system has to be calculated. It represents the sum of the kinetic energies of the composing elements: palm, index, middle, ring, and little fingers and thumb. Because there are only rotational joints, the kinetic energies are computed using equation (3), where q_i is the corresponding joint variable and J_z is the moment of inertia relative to the rotational axis.

$$E_{ci} = \frac{1}{2} J_z \dot{q}_i^2 \qquad (3)$$

The general coordinate system is situated on the wrist and the motion is expressed with respect to it. Every phalange has a moment of inertia relative to the own coordinate system, to its own center of mass, and to the coordinate systems placed between this phalange and the general coordinate system. 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 do not have a homogenous structure, the mass was calculated for an average density of $\rho = 1{,}3 \quad g/cm^3$.

After computing all the necessary moments of inertia and the distances between mass centers of the phalanges and different coordinate systems (which are functions of the joints' variables), the Lagrangean of the hand can be obtained (which has to be derivate, as relation (2) is showing). The resulting dynamic equations have a very complex form [10] and to obtain the solution a specialized tool, MATLAB®, needs to be used [3].

III. THE SIMULATIONS

In order to verify the correctness of the obtained dynamical equations and to visualize the motion of the model, we used the SimMechanics simulation. So we created the model from Fig. 3, which is similar to the kinematical model presented in Fig. 1. The motion of the bodies which compose the SimMechanics model is induced by the existing joints: the wrist having 3 DoFs (implemented using a *Gimbal* block), the metacarpophalangeal joint having 2 DoFs (implemented using a *Cylindrical* block) and the proximal interphalangeal joint and distal interphalangeal joint having only one DoF each (implemented using a *Revolute* block). The last three joints are repeating for every finger.

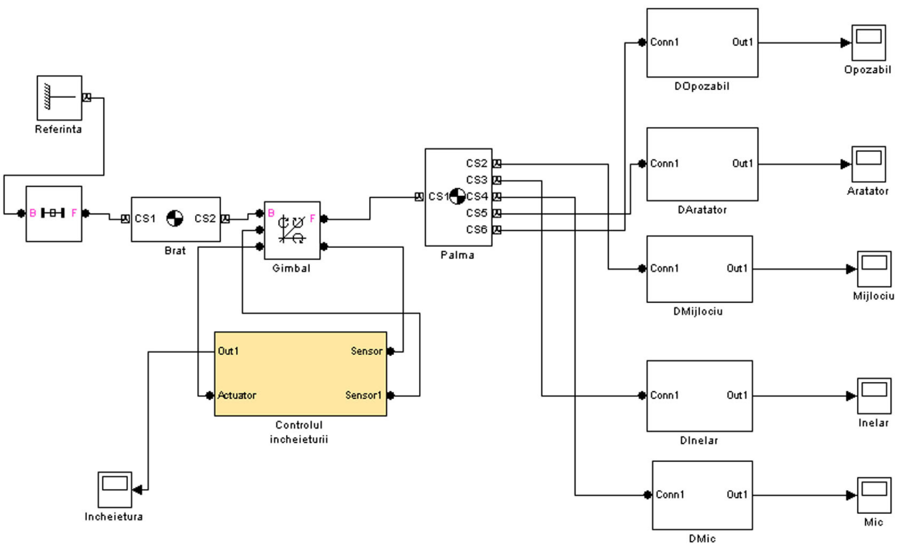

Fig. 3 The SimMechanics model of the hand

The hand cannot make arbitrary gesture due to some natural constraints. The model contains special design blocks to maintain the angular values into the natural range of motion and to compute the torque which appears in joints when grabbing an object. The motion of the joints is captured using joint sensors and plotted using a *Scope* block. All the fingers have a similar structure (Fig. 4), excepting the thumb which has only two phalanges.

To complete the module, we had to specify the lengths, the masses, and the inertial moments with respect to the center of mass for every composing element. Fig. 5 presents the angular values obtained when the hand is grabbing an object of 1 g using the fingertips. The results are very similar with the one obtained in MATLAB [3] (the small differences are due to the specific of SimMechanics model), which proves the correctness of the dynamic equations.

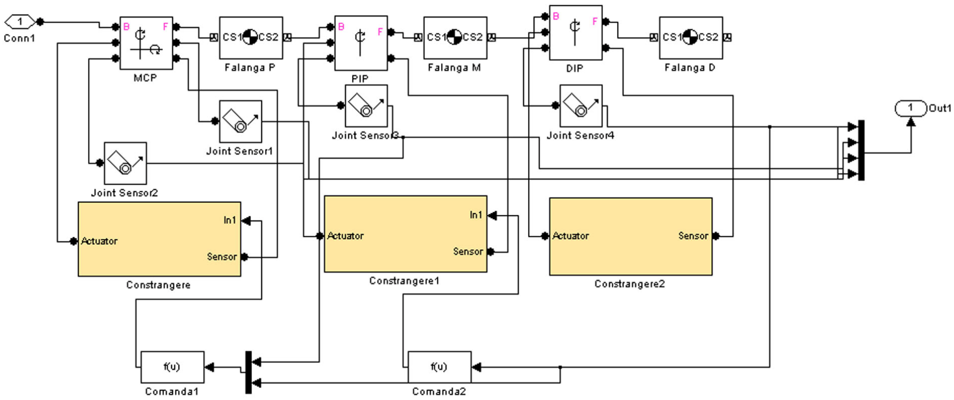

Fig. 4 The structure of a finger

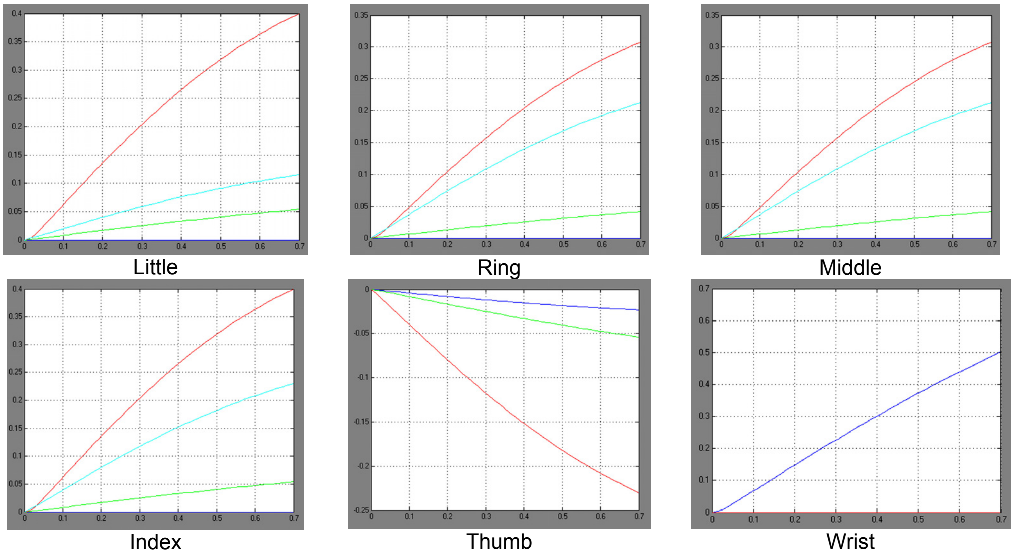

Fig. 5 The angular values when grabbing an object of 1 g

III. CONCLUSIONS

The human hand is a complex mechanism, very difficult to model and to mimic. Because its normal physiological motions require dynamics, the dynamic study is imperative when designing an artificial hand. This paper presents a dynamic model used to design the control of an artificial hand hydraulically actuated. The study of other dynamic models had shown that the most suitable method to create a dynamic model of the human hand is the Lagrange's method combined with Denavit-Hartemberg's convention. The simulation in SimMechanics proved the correctness of the dynamical equations and the results showed the behavior of the system when grabbing objects using only the fingertips.

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