Bond Graph Modeling and Simulation of a Dexterous Hand

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Abstract—This paper presents a methodology for dynamic modeling and trajectory tracking of a dexterous hand. Firstly, the kinematic model is set up based on modified D-H principle. Then we employ an energy-based approach for modeling and its bond graph notation ensures encapsulation of functionality, extendibility and reusability of each element of the model. A toolbox BG V.2.1 in Matlab/Simulink is used for simulation and validation. Simulation results are performed to illustrate the efficacy of the proposed dynamic model.

Keywords—Dexterous hand, bond graph modeling, trajectory tracking

I. INTRODUCTION

Over the past decades, there has been increasingly interest in the challenging field of wheeled mobile manipulators. For creating a robot with dexterous manipulation ability, the study on control of more powerful robots with dexterous hands has attracted significant attention. So far there are many developed multi-fingered hands [1-7]. The project underway pursues the prototype development of a personal assistant robot for assistance tasks in household environments. As a part of the project, this paper presents a methodology for dynamic modeling and trajectory tracking of a dexterous hand.

Modeling is usually treated as a preprocessing stage for the application of a control strategy. Generally speaking, the dexterous hands have been derived based on four approaches: Newton-Euler method, Lagrange's equation, forward recursive formulation, and Kane's approach.

Usually mathematical models are composed of thousands of equations. These models are difficult to create and even more difficult to maintain. Therefore, graphical modeling is generally more suitable for the creation of models of complex systems than equation-based modeling. Bond graph methodology was established by Prof. Henry Paynter in 1961. It is a graphical modeling language for modeling multi-physical systems with a unique representation. Different physical systems such as electrical, mechanical, magnetic, fluid, chemical, and thermodynamic systems can be modeled and linked together. Bond graph theory and notation are well developed and described in [8-10].

Many researchers have worked on bond graph modeling of mechanical systems. Reference [11] explained

how to handle the connected mechanical linkages. Reference [12] studied a comprehensive research on bond graph techniques whose results are applicable to the robotics and spatially moving objects. An omnidirectional mobile robot [13] which is used to be the platform for our robotics project has been modeled using bond graph. In [14] bond graph method has been applied to model an excavating manipulator which is modeled as a 3 DOFs planar manipulator. [15] developed a bond graph model for a prosthetic mechanism — a thumb prosthesis with capabilities to move and do a large class of manipulative tasks. Contact interaction of the prosthetic mechanism with a rigid object has been modeled. In [16] the Word Bond Graph Objects (WBGO) have been used to model the dynamics of a hand prosthesis system.

In this work, we systematically develop a bond graph model for the dexterous hand. The rest of the paper is organized as follows. In Section II we introduce the mechanical structure of a dexterous hand. In Section III the kinematic model is established based on modified D-H principle. Section IV provides the bond graph modeling process for the whole hand. A control system is presented and a simulation case for trajectory tracking is analyzed in Section V. A toolbox BG V.2.1 in Matlab/Simulink is used for the simulation and the validation. The complete robot simulation structure is implemented in Simulink. Finally, Section VI concludes with the main points made in this paper.

II. MECHANICAL STRUCTURE DESIGN

In our project the dexterous hand which has the similar configuration with the human hand is composed of five fingers. Fig. 1 shows the structure of this robotic hand. As can be seen in this figure, each finger contains four joints. Among these five fingers, the last two fingers (the ring and the little fingers) are mechanically coupled so that they keep the same motion. Therefore these two fingers just have 4 degrees of freedom (DOFs) and the little finger only plays a supportive role. Thus, this hand totally has sixteen DOFs, due to the five fingers, assuming no extra DOFs in the palm. This design can achieve the dexterity of human hand such that it can be used to perform various operations.



Fig. 1. Structure of dexterous hand (a) Solidworks drawing and (b) Dimensions

The model drawn in Solidworks is shown in Fig.1 (a). This hand's size and shape of each part are created as size and shape of the actual component. To reduce the complexity, only the mechanical parts are included in the Solidworks drawing. This structure is sufficient to reflect the physical properties of the dexterous hand.

Normally, one DOF needs an independent motor to drive its motion. According to the actuator system, robot hands usually can be divided into two types: built-in actuator type and external actuator type. We choose the former one which drives the joint by direct drive. The independent joints of each finger are equipped with appropriate actuators.

III. KINEMATICS ANALYSIS

Before the bond graph modeling, the kinematic model is briefly discussed.



Fig. 2. Finger linage (a) Definition of reference frames (b) Geometry of a finger module

Each finger is an independent kinematic linkage with four DOFs. This kinematic linkage consists of four rigid bodies connected to each other by joints. Fig. 2 shows this linkage and illustrates the coordinate frame of each joint. Each rigid body is referred to as a link, denoted by A. Let A_1 , A_2 , A_3 , A_4 denote four links. The kinematic analysis mainly includes two sides, one is the forward kinematic analysis. The forward kinematic analysis means that the location and pose of a fingertip in a given coordinate reference system can be worked out with the given geometry parameters of the links and the variables of the joints for a finger. Let $q_{fi} = \{q_{fi1}, q_{fi1}, q_{fi3}, q_{fi4}\}$ denote the set of rotational joint angles of finger *i*, and then q_{fi} yields an acceptable position and orientation of the links in the chain

by using the homogeneous transformation matrix. Given the matrix ${}^{i-1}T_i$ expressing the difference between the coordinate frame of A_{i-1} and the coordinate frame of A_i , the application of ${}^{i-1}T_i$ transforms any point in A_{i-1} to the body frame of A_i . Repeating the above procedure, the location of any point $\begin{bmatrix} x & y & z \end{bmatrix}^T \in A_4$ in the world frame is determined by multiplying the transformation matrices:

$$\begin{bmatrix} x' & y' & z' & 1 \end{bmatrix}^{T} = {}^{0}T_{1} {}^{1}T_{2} {}^{2}T_{3} {}^{3}T_{4} \begin{bmatrix} x & y & z & 1 \end{bmatrix}^{T}$$
(1)
= $T \begin{bmatrix} x & y & z & 1 \end{bmatrix}^{T}$

where
$$T = \begin{bmatrix} {}^{0}R_{4} & {}^{0}P_{4} \\ 0...0 & 1 \end{bmatrix} = \begin{bmatrix} n_{x} & o_{x} & a_{x} & p_{x} \\ n_{y} & o_{y} & a_{y} & p_{y} \\ n_{z} & o_{z} & a_{z} & p_{z} \\ 0 & 0 & 0 & 1 \end{bmatrix} \in \Re^{4 \times 4}$$
,

$${}^{0}R_{4} = \begin{bmatrix} n_{x} & a_{x} \\ n_{y} & o_{y} & a_{y} \\ n_{z} & o_{z} & a_{z} \end{bmatrix} \in \Re^{3 \times 3}$$
 and

 ${}^{0}P_{4} = \begin{bmatrix} p_{x} & p_{y} & p_{z} \end{bmatrix}^{T} \in \Re^{3}$ give the rotation axis and the position in the base frame, respectively.

The above formula represents the forward kinematics for positioning a linkage by a specific joint configuration. The Modified Denavit-Hartenberg method [17] (MDH) is used to analyze the kinematics. Fig. 3 shows the modified form of Denavit-Hartenberg, where frame i-1 has its origin along the axis of joint i-1 and frame i has its origin along the axis of joint i. This form is commonly used in literature dealing with robot kinematics.



Fig. 3. Modified form of Denavit-Hartenberg

Its kinematic equations could be expressed by the following equations:

$${}^{i-1}T_{i} = Rot(x, \alpha_{i-1}) \times Trans(x, a_{i-1}) \times Rot(z, q_{i}) \times Trans(z, d_{i})$$
$${}^{i-1}T_{i} = \begin{bmatrix} \cos q_{i} & -\sin q_{i} & 0 & a_{i-1} \\ \sin q_{i} \cos \alpha_{i-1} & \cos q_{i} \cos \alpha_{i-1} & -\sin \alpha_{i-1} & -d_{i} \sin \alpha_{i-1} \\ \sin q_{i} \sin \alpha_{i-1} & \cos q_{i} \sin \alpha_{i-1} & \cos \alpha_{i-1} & d_{i} \cos \alpha_{i-1} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where

 α_{i-1} = the angle between Z_{i-1} and Z_i measured about X_{i-1} a_{i-1} = the distance from Z_{i-1} to Z_i measured along X_{i-1} q_i = the angle between X_{i-1} and X_i measured about Z_i d_i = the distance from X_{i-1} to X_i measured along Z_i

Considering the fingertip as the end point, the forward kinematics of the finger is derived by the MDH method. The parameters of all the links and the joints are depicted in Table 1.

Link	α	а	q	d
0-1	90°	0	90°	0
1-2	90°	h_{f_1}	0°	0
2-3	0°	h_{f_2}	0°	0
3-4	0°	h_{f_3}	0°	0

The inverse formula of (1) forms inverse kinematics problem in which a set of joint angles needs to be calculated corresponding to a given spatial constraint of the fingertip.

IV. BOND GRAPH MODELING

This section presents the activities related to bond graph modeling of the whole dexterous hand. For the sake of clarity, first, the concept of bond graph is discussed. Associated with each bond are power conjugates, effort and flow, the product of which is the instantaneous power flowing to or from physical elements. Efforts and flows in mechanical systems are forces and velocities. Energy dissipation is modeled by resistive element **R**, energy storage devices such as springs and inertia are modeled by elements C and I, sources of efforts and flows are represented by Se and Sf, and power transformations are modeled by transformers TF or gyrators GY. Power bonds join at 0 junctions summing flows to zero with equal efforts or at 1 junctions summing efforts to zero with equal flows, which implements Newton's 2nd law. Bond graphs have many advantages. Multiphysic dynamic systems such as electrical, mechanical, magnetic, chemical, and thermodynamic systems can be modeled and linked together. Bond graph is an energy-based modeling technique with modularity that permits system growth.

Note that the dexterous hand is a complex electromechanical system. This method is suitable for the modeling. The modeling process of a finger contains four steps: modeling an electromechanical system, modeling joints, modeling links and Eulerian Junction Structure (EJS).

A. Modeling of Electromechanical System

An electromechanical system can be considered as a concatenation of four parts: electrical part of DC motor, mechanical part of DC motor, gear set and load part. The word bond graph model is given by Fig. 4. Fig. 5 describes the bond graph model of the electromechanical part. The

electrical part consists of three components resistance R_a , inductance L_a and an input effort source U which represents the voltage source of the motor. The gyrator GY describes the electromechanical conversion in the motor. The mechanical part is characterized by its inertia I_a and viscous friction coefficient B_m . The transmission elasticity of the shaft is represented by the element C = 1/K. *TF* with a reducer constant k_r models the gearbox. The load part (joint) is characterized by its inertia J and viscous friction coefficient B.



Fig. 4. Word bond graph of electromechanical system



Fig. 5. Schematic of electromechanical system

B. Modeling of a Hand

As mentioned above, the dexterous hand is composed of five independent chains of rigid bodies (links) connected by joints. Thus, the bond graph model of the dexterous hand can be considered as a combination of five independent bond graph models of the fingers.

1) Modeling of Joint

For modeling a joint, it is decided only to model the transfer of energy in a joint. Therefore, the following behavior has explicitly been neglected: (1) friction in the joint, and (2) energy storage in the joint.

Since a joint establishes a connection between two links, it imposes a relation between the angular velocities and the moments of the two bodies. A torque applied in a joint is applied between the two connected links and, in fact, applies the same torque to both links. This specifies the relation between the torque applied by the actuator (${}^{i}\tau_{acti}$) and the torques applied to the connected links (${}^{i}\tau_{iointi,i-1}$ and ${}^{i}\tau_{iointi,i}$):

$${}^{i}\tau_{acti} = {}^{i}\tau_{joint\,i,i-1} = {}^{i}\tau_{joint\,i,i} \tag{2}$$

On the other hand, there is a relation between the angular velocities of ${}^{i}\omega_{i-1}$ and ${}^{i}\omega_{i}$. Just as with other flow type variables the following relation holds:

$${}^{i}\omega_{i} = {}^{i}\omega_{i-1} + {}^{i}\omega_{acti} \tag{3}$$

In this paper ${}^{i}a_{j}$ denotes the value *a* of link *j* expressed in frame *i*. Thus ${}^{i}\omega_{i}$ and ${}^{i}\omega_{i-1}$ are respectively the angular velocity of link *i* expressed in frame *i* and the angular velocity of link *i*-1 expressed in frame *i*. ${}^{i}\omega_{acti}$ denotes the angular velocity generated by the motor. The above two relations are represented by 0-junction in the bond graph language described in Fig. 6 (a) and (b).



Fig. 6. Bond graph of a joint (a) effort source and (b) flow source

2) Modeling of Link



Fig. 7. Velocity relation between links

The velocities of link *i* are completely determined by the velocities of link *i*-1 and the motion of joint *i*. Fig. 7 describes the velocity relation between links. These relations can be expressed by (4), (5) and (6).

Angular velocity of link i

$${}^{i}\omega_{i} = {}^{i}R_{i-1}({}^{i-1}\omega_{i-1} + {}^{i-1}\omega_{acti})$$
(4)

Translational velocity of link *i*:

$${}^{i}v_{ci} = {}^{i}R_{i-1}{}^{i-1}v_{i} + \tilde{r}_{i,ci}{}^{i}\omega_{i}$$
(5)

$${}^{i}v_{i+1} = {}^{i}v_{ci} + \tilde{r}_{ci,i+1}{}^{i}\omega_{i}$$
(6)

where c_i denotes the center of mass of link *i*; point *i* and i+1 denote the i_{ih} and $(i+1)_{ih}$ connection points between links; ${}^{i-1}\omega_{i-1}$ is the angular velocity of link i-1 expressed in frame i-1; ${}^{i}v_{ci}$, ${}^{i-1}v_{i}$ and ${}^{i}v_{i+1}$ are the linear velocities of the centre of mass of link *i* expressed in frame *i*, frame origin of link *i* expressed in frame i-1 and frame origin of link *i* +1 relative to frame *i* respectively; ${}^{i}R_{i-1}$ is the rotation matrix between frames *i* and i-1; $r_{i,ci}$ is a vector from point *i* to point *ci*; similarly, $r_{ci,i+1}$ is a vector from point *ci* to point *i*+1.

The skew-symmetric matrices \tilde{r} is built from r such that

$$r = \begin{bmatrix} r_1 \\ r_2 \\ r_3 \end{bmatrix}, \tilde{r} = \begin{bmatrix} 0 & r_3 & -r_2 \\ -r_3 & 0 & r_1 \\ r_2 & -r_1 & 0 \end{bmatrix}$$

3) Newton-Euler Equations



Fig. 8. Force relation between links

Fig. 8 shows link *i* together with all forces and torques acting on it. In this figure, m_i is the mass of link *i* and ig_i is the gravitational acceleration expressed in frame *i*. By the law of action and reaction ${}^if_{i-1,i}$ and ${}^if_{i+1,i}$ are respectively the force acting from link (*i*-1) on link *i* and the force acting from link (*i*+1) on link *i* expressed in frame *i*. As shown in (2), ${}^i\tau_{joint,i}$ and ${}^i\tau_{joint,i+1,i}$ are the torques applied by the actuator relative to frame *i*. When all vectors in Fig. 8 are expressed in frame *i*, the total force and torque applied to a link can be stated as

Total force applied to a link:

$${}^{i}F_{i} = {}^{i}f_{i-1,i} + {}^{i}f_{i+1,i} + m_{i}{}^{i}g_{i}$$
⁽⁷⁾

Total torque applied to a link:

$${}^{i}\tau_{i} = {}^{i}\tau_{joint\,i,i} + {}^{i}\tau_{joint\,i+1,i} + \tilde{r}_{i,ci} {}^{i}f_{i-1,i} + \tilde{r}_{i+1,ci} {}^{i}f_{i+1,i}$$
(8)

4) Eulerian Junction Structure in 3D Mechanical Systems

From (7) and (8), the coordinates of the forces and the torques are all written relative to a body-fixed frame attached at the center of mass instead of with respect to an inertial frame. In this way, the inertial tensor remains constant. Hence, we can formulate the d'Alembert

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principle in a body-fixed coordinate system without updating the inertial tensor. However, we now must calculate the relative coordinate transformations across joints. We must also take into account the gyroscopic torques and forces that result from formulating the d'Alembert principle in an accelerated frame. The nonlinear differential equations (9) known as Newton-Euler's equations derived by applying D'Alembert principle represent the body motion in the 3D local frame.

$${}^{i}\tau_{ix} = {}^{i}J_{ixx}{}^{i}\dot{\omega}_{ix} + {}^{i}\omega_{iy}{}^{i}J_{izz}{}^{i}\omega_{iz} - {}^{i}\omega_{iz}{}^{i}J_{iyy}{}^{i}\omega_{iy}$$

$${}^{i}\tau_{iy} = {}^{i}J_{iyy}{}^{i}\dot{\omega}_{iy} + {}^{i}\omega_{iz}{}^{i}J_{ixx}{}^{i}\omega_{ix} - {}^{i}\omega_{ix}{}^{i}J_{izz}{}^{i}\omega_{iz}$$

$${}^{i}\tau_{iz} = {}^{i}J_{izz}{}^{i}\dot{\omega}_{iz} + {}^{i}\omega_{ix}{}^{i}J_{iyy}{}^{i}\omega_{iy} - {}^{i}\omega_{iy}{}^{i}J_{izz}{}^{i}\omega_{iz}$$

$${}^{i}F_{iz} = m_{i}{}^{i}\dot{v}_{cix} + m_{i}{}^{i}\omega_{iy}{}^{i}v_{ciz} - m_{i}{}^{i}\omega_{iz}{}^{i}v_{ciy}$$

$${}^{i}F_{iy} = m_{i}{}^{i}\dot{v}_{ciy} + m_{i}{}^{i}\omega_{iz}{}^{i}v_{ciy} - m_{i}{}^{i}\omega_{ix}{}^{i}v_{ciz}$$

$${}^{i}F_{iz} = m_{i}{}^{i}\dot{v}_{ciz} + m_{i}{}^{i}\omega_{ix}{}^{i}v_{ciy} - m_{i}{}^{i}\omega_{iy}{}^{i}v_{ciz}$$

where ${}^{i}F_{ix,iy,iz}$ are the components of ${}^{i}F_{i}$, ${}^{i}\tau_{ix,iy,iz}$ are the components of ${}^{i}\tau_{i}$ and ${}^{i}J_{ixx,iyy,izz}$ are the components of ${}^{i}J_{i}$ which is the moment of inertia of link *i* about its center of mass. All the forces ${}^{i}F_{ix,iy,iz}$, the torques ${}^{i}\tau_{ix,iy,iz}$ and the inertial tensor ${}^{i}J_{ixx,ivy,izz}$ are written relative to the bodyfixed frame. ${}^{i}F_{i}$ and ${}^{i}\tau_{i}$ have been derived in (7) and (8).

Euler's equations for the rotation of a rigid body contain a term with an exterior product between the momentum and the angular velocity. This term is associated with the gyroscopic moments M_{gyro} . The common bond graph representation of this exterior product in Euler's equations is the EJS. For the torques it is denoted by EJS-T:

$$M_{gyro-T} = {}^{i}\omega_{i} \times {}^{i}J_{i}{}^{i}\omega_{i}$$
(10)

where

here
$${}^{i}J_{i} = \begin{bmatrix} {}^{i}J_{ixx} & 0 & 0\\ 0 & {}^{i}J_{iyy} & 0\\ 0 & 0 & {}^{i}J_{izz} \end{bmatrix}$$

 $\boldsymbol{\varphi} = \begin{bmatrix} {}^{i}\boldsymbol{\omega}_{ix} & {}^{i}\boldsymbol{\omega}_{ix} & {}^{i}\boldsymbol{\omega}_{ixz} \end{bmatrix}^{T}.$

From (10), the following expression can be derived:

$$M_{gyro-T} = \begin{bmatrix} M_1 \\ M_2 \\ M_3 \end{bmatrix} = \begin{bmatrix} 0 & {}^{i}J_{izz} & i\omega_{iz} & -{}^{i}J_{iyy} & i\omega_{iy} \\ -{}^{i}J_{izz} & i\omega_{iz} & 0 & {}^{i}J_{ixx} & i\omega_{ix} \\ {}^{i}J_{iyy} & i\omega_{iy} & -{}^{i}J_{ixx} & i\omega_{ix} & 0 \end{bmatrix} \begin{bmatrix} i\omega_{ix} \\ i\omega_{iy} \\ i\omega_{iz} \end{bmatrix} (11)$$
$$= X ({}^{i}J_{i} & {}^{i}\omega_{i})^{i}\omega_{i}$$

Similarly, the EJS for the forces called EJS-F is as (12):

$$M_{gvro-F} = {}^{i}\omega_{i} \times m_{i} {}^{i}v_{ci}$$
(12)

where ${}^{i}v_{ci} = \begin{bmatrix} {}^{i}v_{cix} & {}^{i}v_{ciy} & {}^{i}v_{ciz} \end{bmatrix}^{T}$.

In multiband notation, it has been shown that the EJS may be represented by a nonlinear three-port gyrator.



Fig. 9. Nonlinear 3-port gyrator composition of EJS

Fig. 10 shows the detailed bond graph representations according to the Newton-Euler's equations.





Fig. 10. Bond graph model of the Newton-Euler's equations (a) EJS-T (b) EJS-F

5) Bond Graph Modeling of a Link with a Joint

The bond graph model of a link including a joint module is illustrated in Fig. 11. This model is derived based on the exchange of power and movement between the constituents of the physical system corresponding to the Newton-Euler formulation. To represent the dynamics of a link with a joint, the bond graph of Fig. 11 is augmented with inertia elements, and the linear velocity of

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and

the centre of mass is described. First, an external velocity source Sf is supposed to act on the 0-junction as the motor angular velocity. At the left side the diagonal moment of inertia matrix ${}^{i}J_{i}$ is connected as an I-element to the ljunction of the rotational velocities in the body frame. At the right side the mass matrix m_{i} is connected as an Ielement to the l-junction of the translational velocities in the body-fixed frame, together with the gravity force source Se. The gyroscopic forces which act between these velocities are represented by the modulated gyrator MGY. Because the Euler equations represent these forces, the MGY is referred to as an EJS. The meanings of all the transformers MTF are shown in Fig. 11.



Fig. 11. Bond graph representing the dynamics of link i

6) Bond Graph Modeling of a Finger

In this paper, a finger consists of four joints. The simplified bond graph of a finger is shown in Fig. 12; similar graphs are implemented on the other fingers.



Fig. 12. Model of finger kinematic chain

A bond graph model of this kinematic chain can be established through the connection of the links and the joints. And based on the analysis in Section 4, the joints and the links as the submodels in Fig. 12 can be replaced by Fig. 5, Fig. 11 respectively. As a rigid body, the bond graph of each link also should connect with EJS which is shown in Fig. 9 and Fig. 10. The flow sources are the translational velocity and the rotational velocity of the base frame Σ_{si} of finger *i* attached to the palm. These velocities are dependent on the velocity of the palm and the position of frame Σ_{si} in the palm frame Σ_{p} . In this paper the palm is assumed to be fixed.

7) Bond Graph Modeling of a Whole Hand

The fingers are mounted on the palm directly. Therefore, once the bond graph model of every single finger is known, the bond graph model of the hand with respect to the palm can be easily constructed on the basis of the constant homogeneous matrices corresponding to the coordinate transformations between the base frames of the five fingers and the palm. Fig. 13 illustrates the bond graph model of the whole dexterous hand with five fingers.



Fig. 13. Model of the whole hand

V. VALIDATION OF BOND GRAPH MODEL

In this paper, a toolbox BG V.2.1 in Matlab/Simulink is used for simulation and validation. Though many bond graph-based simulation software packages are available, at academic institutions level and in most industries, Matlab/Simulink is the software which is used more often for studying dynamical systems. Using this toolbox the bond graph model is directly built in Simulink. This toolbox only consists of 9 blocks which realize the whole necessary functionality. Fig. 14 shows the bond graph model of one link using this toolbox. By comparison, it is clear that this model is consistent with the model shown in Fig. 11.



Fig. 14. Bond graph model of using BG V.2.1

For the validation of this bond graph model, we use the precise mathematical model to construct an open-loop control system. The dynamics of each finger can be obtained using the Lagrangian approach in the form:

$$M_{f_i}(q_{f_i})\dot{q}_{f_i} + C_{f_i}(q_{f_i}, \dot{q}_{f_i})\dot{q}_{f_i} + N_{f_i}(q_{f_i}, \dot{q}_{f_i}) = \tau_{f_i} \quad (13)$$

where

 q_{f_i} : the joint vector of finger *i*,

 M_{f} : the acceleration-related inertia matrix term,

 C_{f} : the Coriolis and Centrifugal matrix,

 N_{f} : the friction and gravity vector,

 τ_{f} : driving torque applied on each joint.

Assume the parameters are all known, we have obtained the precise mathematical dynamic model of the fingers which has the same form as the above equation. Through this equation we calculate the torques of driving motors. We now apply these torques as the inputs of the bond graph model to track a reference trajectory. The reference joint trajectory for a finger is given as: $\left[q_{f11} \quad q_{f12} \quad q_{f13} \quad q_{f14}\right]^T = \left[0.25t^2 \quad 0.2t^2 \quad 0.15t^2 \quad 0.1t^2\right]^T$



Fig. 15. Simulation results (a) joints trajectories and (b) joints torques

The several output results of the bond graph are shown. In Fig. 15 (a), it gives each finger's trajectory. In Fig. 15 (b), the torques obtained from the mathematical model are shown. It has been clearly observed from the above figures that the results from bond graph model are in accordance with the theoretical analysis and the desired trajectory is well tacked through the open-loop control system. The simulation results have shown the effectiveness of the bond graph model of one finger. The other fingers' models can be validated by the same method.

VI. CONCLUSIONS

The objective of this paper is to introduce an approach for constructing a bond graph model of a dexterous hand. We have presented a step by step procedure for the bond graph modeling of this hand. The complete robot simulation structure is implemented in Simulink. The model has been validated under an open-loop controller through the precise mathematical model to show its effectiveness. It is proved that the application of bond graph facilitates the modeling of this complex electromechanical system, as well as the extension of a control system.

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