Toward a Dynamic Model of Robotic Marionettes

Nguyen Kim Doang, Lim Kwang Yong, Dong Wei, Goh Young Koon, Chen I-Ming, Yeo Song Huat, Henry Been-Lirn Duh[1], Li Kang, Su Chen Hao

School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore

[1] Department of Electrical and Computer Engineering, National University of Singapore, Singapore

***Abstract*—Robotic marionettes are those mechatronic system in which strings that control motion of a puppet are driven by a puppeteer platform including motor-pulley modules. Systematic control of robotic marionettes is now still a tough problem, which several research groups have been attempting to solve. In this paper, we present dynamic models of the robotic marionette developed from Lagrange equation. Feed-forward control and feedback control are studied based on the dynamic models with the illustration of block diagrams. A process of identifying the parameters appearing in the dynamic models is presented in details. The modeling provides better insight of the system, and builds a mathematical platform to research the control and simulation of the marionette system.**

***Keywords*—dynamics, modelling, robotic marionette**

I. INTRODUCTION

Marionette is a traditional art which exists in some cultures, but seeing a sharp decrease in popularity due to the arising of new type of entertainment. Many efforts have been made in order to maintain this art in various countries. Approaching to this motivation, but from different point of view, researchers have been exploring the ability of integrating current technologies in robotics into marionette performance for bringing new colors to this traditional art.

In his very early work on developing a robotic marionette, Hoffmann introduced a computerized controlled life-size marionette, whose mobility is twelve mechanical degrees of freedom [1]. The marionette is controlled by a mechatronic rucksack to perform some simple choreographic motions. Hemami, et al. [2], proposed a strategy for stability of a marionette under a system of unidirectional muscle-like actuators. The strategy provides positive force and positive input to the actuators which are analogous to functions of the firing rate of natural muscles. Yamane et al. controlled the upper body of a marionette to perform some dances using human motion [3]. A feed-forward controller was applied to prevent swinging problem of the puppet hands. Recently Johnson and Murphey presented a mixed dynamic-kinematic modeling technique that removes the controller dynamics from the marionette, resulting in a clean abstraction that represents the dynamics of the marionette in a natural way [4].

Perhaps the most developed robotic marionette project is RObotic Marionette System (ROMS) by Chen, et al [5], [6]. The designs of ROMS versions (ROMS I, II, III) were inspired by both Western and Eastern puppetry. The stationary assembly of motors and pulleys in modular forms is allusive to Gou Pai, in which all strings are connected to one control platform. ROMS is capable of various highly articulated motions due to its high number of DOF. Low and high-level motor control enables the creation of gross and fine motion in the marionette. Nguyen et al proposed a motion mapping algorithm to map human motion into marionette motion. This technique allows him to use captured human motion to control ROMS III in real-time [7]. Some other works on motion planning for marionette can be found in [4],[8].

Though quite a few works were carried out, none of them presented a systematic research on the dynamic model of the control system of a robotic marionette. In this work, we propose preliminary dynamic models of the robotic marionette developed from Lagrange equation. Feed-forward control and feedback control are studied based on the dynamic models with the illustration of block diagrams. A process of identifying the parameters appearing in the dynamic models is presented in details. The modeling provides better insight of the system, and builds a mathematical platform to research the control and simulation of the marionette system.

II. MARIONETTE SYSTEM DYNAMICS

A. Inverse dynamics model

The inverse dynamic model provides the motor torques and forces in term of string-space variables, such as positions, velocities and accelerations. The model allows us to identify dynamic parameters that are necessary for both control and simulation, to compute the actuator torques needed for the robotic system to achieve desired motions, and also to select relevant actuators in mechanical system design. The inverse dynamic model is described by

$$\Gamma = f\left(q^s, \dot{q}^s, \ddot{q}^s, f_e\right)$$

In which, Γ is the vector of actuator torques

$q^s, \dot{q}^s, \ddot{q}^s$ is the vectors of string-space variables, including positions, velocities and accelerations

f_e is the vector of forces and moments exerted by the robotic marionette on environment

We can model the above function by Lagrange equation:

$$\Gamma = I(q^s)\ddot{q}^s + V(\dot{q}^s, q^s)\dot{q}^s + G(q^s) \qquad \text{(E1)}$$

In which $V(\dot{q}^s, q^s)$ is the matrix of centrifugal, Coriolis and viscous effects in general.

$G(q^s)$ is the matrix of gravitational effect.

This equation represents the general form of the inverse dynamic model of the robotic marionette system.

B. Direct dynamics model

The direct dynamic model describes the string accelerations in term of the string positions, velocities and the toques at the actuators. It is employed to carry out simulation for the sake of testing the performance of the robot and to study the relative merits of possible control laws. During simulation, the dynamic equations are solved for the string acceleration given the input torques, and the current string positions and velocities. Then through integrations of the acceleration, the link trajectories can be determined. The general equation of the direct dynamic model is represented by the relation

$$\ddot{q}^s = h\left(q^s, \dot{q}^s, \Gamma, f_e\right)$$

Now from equation (E1), we separate $I(q^s)$ into two components $I_d\left(q^s\right)$ and $\Delta I\left(q^s\right)$, where $I = \begin{pmatrix} I_{11} & \cdots & I_{1n} \\ \vdots & \ddots & \vdots \\ I_{m1} & \cdots & I_{mn} \end{pmatrix}$ is the matrix of inertial effects in the inverse dynamic equation, and $I_d = \begin{pmatrix} I_{11} & 0 & \cdots & 0 \\ 0 & I_{22} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & I_{nn} \end{pmatrix}$ is the diagonal matrix of I.

So $\quad I\left(q^s\right) = \Delta I\left(q^s\right) + I_d\left(q^s\right)$

Plug this into inverse dynamic equation (E1), we get

$$\left[I_d\left(q^s\right) + \Delta I\left(q^s\right)\right]\ddot{q}^s + V\left(\dot{q}^s, q^s\right)\dot{q}^s + G\left(q^s\right) = \Gamma$$

Let $\quad d = \Delta I\left(q^s\right)\ddot{q}^s + V\left(\dot{q}^s, q^s\right)\dot{q}^s + G\left(q^s\right) \qquad$ (E2)

We have $\quad I_d\left(q^s\right)\ddot{q}^s + d\left(\ddot{q}^s, \dot{q}^s, q^s\right) = \Gamma$, or

$$\ddot{q}^s = I_d^{-1}\left(q^s\right)\left(\Gamma - d\right) \qquad \text{(E3)}$$

Equation (E3) represents the direct dynamic model of the robotic marionette system.

Based on equations (E2) and (E3), the below block diagram can be obtained (refer to Figure 1)

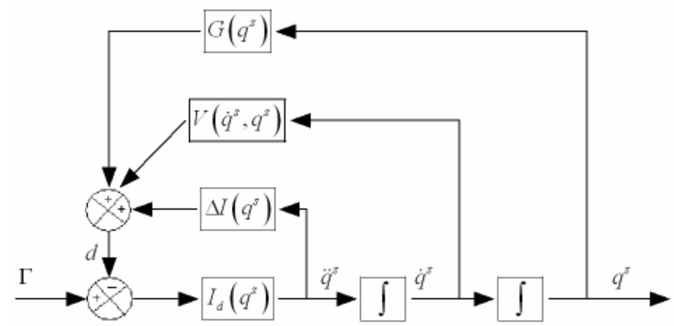

Figure 1 Direct dynamic model block diagram

C. Marionette dynamics model

In this section we will derive the specific inverse dynamic model for our marionette system.

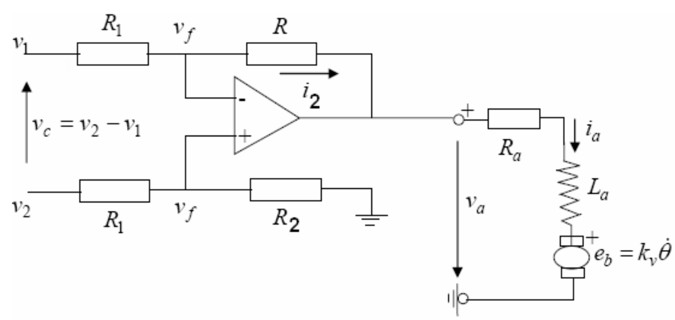

Figure 2 Motor control circuit

From the electric circuit of the motor control in Figure 2, the control voltage is calculated as

$$v_c = \frac{R_1}{R_2}\left(R_a i_a + L_a \frac{di_a}{dt} + K_v \dot{\theta}\right)$$

We also have the relationship: $\Gamma = K_t i_a$

So $\quad v_c = \frac{R_1}{R_2}\left[R_a\left(\frac{\Gamma}{K_t}\right) + L_a \frac{d}{dt}\left(\frac{\Gamma}{K_t}\right) + K_v \dot{\theta}\right]$

Which means $\quad v_c - \frac{R_1 K_v}{R_2}\dot{\theta} = \frac{R_1 R_a}{R_2 K_t}\Gamma + \frac{R_1 L_a}{R_2 K_t}\frac{d\Gamma}{dt}$

In term of string i[th]'s variables:

$$v_{ci} - \frac{R_{1i} K_{vi}}{R_{2i}}\dot{q}_i^s = \frac{R_{1i} R_{ai}}{R_{2i} K_{ti}}\left(\Gamma_i + \frac{L_{ai}}{R_{ai}}\frac{d\Gamma_i}{dt}\right) \qquad \text{(E4)}$$

With v_{ci} is the applied voltage from the controller on the motor that drive the string i[th].

Now let $K_{ei} = \frac{R_{1i}K_{vi}}{R_{2i}}, \quad K_{mi} = \frac{R_{2i}K_{ti}}{R_{1i}R_{ai}}, \quad \tau_{mi} = \frac{L_{ai}}{R_{ai}}$

(K_{mi} is torque-velocity gain, τ_{mi} is motor's time constant)

Laplace transform of equation (E4) gives the following s-domain equation

$$\left(v_{ci}(s) - K_{ei}\dot{q}_i^s(s)\right) = \frac{1}{K_{mi}}\left(\Gamma_i + \tau_{mi}s\Gamma_i\right)$$

i.e. $$\Gamma_i(s) = \frac{K_{mi}}{(1+\tau_{mi}s)}\left(v_{ci}(s) - K_{ei}\dot{q}_i^s(s)\right) \quad \text{(E5)}$$

The above equation describes the relation between the torque at the motor driving the string ith and the respective string velocity and control voltage. In other to obtain a complete equation describe the dynamics of the whole system; we combine those individual equations in to a unique one by state-space representation.

Now let

$$\tau_m = \begin{pmatrix} \frac{K_{m1}}{(1+\tau_{m1}s)} & 0 & \cdots & 0 \\ 0 & \frac{K_{m2}}{(1+\tau_{m2}s)} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \frac{K_{mn}}{(1+\tau_{mn}s)} \end{pmatrix},$$

and $$K_e = \begin{pmatrix} K_{e1} & 0 & \cdots & 0 \\ 0 & K_{e2} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & K_{en} \end{pmatrix}$$

Equation (E5) results in

$$\Gamma(s) = \tau_m\left(v_c(s) - K_e\dot{q}^s(s)\right) \quad \text{(E6)}$$

Combine the equation (E2), (E3) and (E6), we have the below block diagram (Figure 3), which is so-called Marionette System Dynamics.

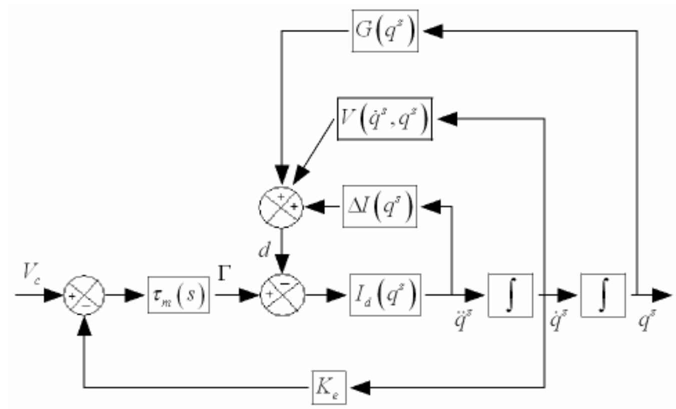

Figure 3 Marionette system dynamics block diagram

III. OPEN-LOOP CONTROL MODEL

An open-loop control system is controlled directly, and only, by an input signal, without the benefit of feedback. The basic units of this system are an amplifier and a motor. The amplifier receives a low- level input signal and amplifies it enough to drive the motor to perform the desired job. Open-loop control systems are not as commonly used as closed-loop control systems because they are less accurate. A typical property of the open-loop control system is that it does not use feedback information to determine whether the inputs have achieved the desired task. This means that the outputs of the processes, which the system is controlling, are not being observed. As a result, an open-loop control system actually can not engage in machine learning and also cannot compensate for any errors that arise during its operation. It also may not eliminate disturbances in the system. Open-loop control is useful for well-defined systems where the relationship between input and the resultant state can be modeled by a mathematical formula.

Equation (E2) gives:

$$\underset{\sim}{d} = \Delta I\left(\underset{\sim}{q}^s\right)\underset{\sim}{\ddot{q}}^s + V\left(\underset{\sim}{\dot{q}}^s, \underset{\sim}{q}^s\right)\dot{q}^s + G\left(\underset{\sim}{q}^s\right) \quad \text{(E7)}$$

Where the sigh ~ under the variables to imply the desired value.

Equation (E3) gives: $\underset{\sim}{\Gamma} = I_d\left(\underset{\sim}{q}^s\right)\underset{\sim}{\ddot{q}}^s + \underset{\sim}{d}$ (E8)

Equation (E6) gives: $v_c(s) = \tau_m^{-1}\underset{\sim}{\Gamma}(s) + K_e\underset{\sim}{\dot{q}}^s(s)$ (E9)

Equations (E2), (E3), (E6), (E7), (E8) and (E9) altogether construct the block diagram of the open-loop control system as shown in Figure 4.

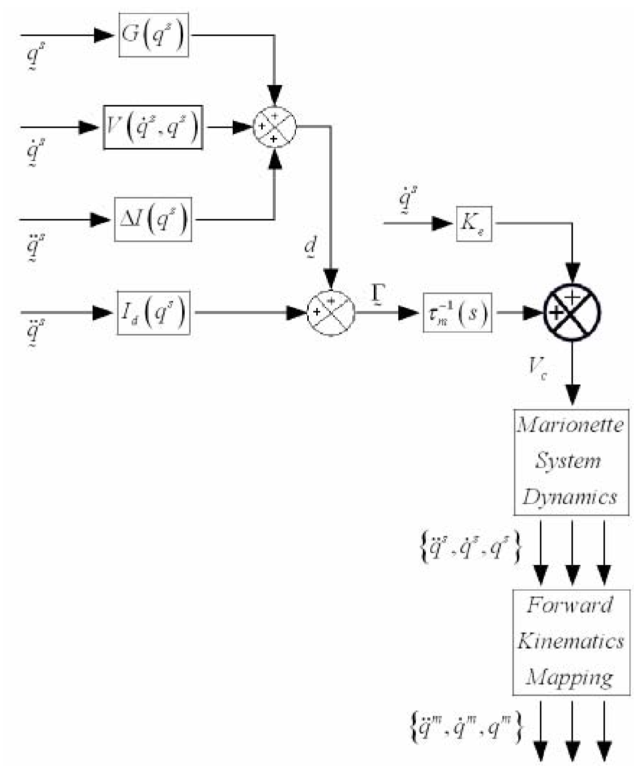

Figure 4 Open-loop control block diagram

IV. STRING-SPACE CLOSED-LOOP CONTROL MODEL

For open-loop control systems which suffer significant disturbances and parameter variation, the performance may be seriously affected. The difference between marionette input and output, so-called the system error, becomes larger. The system stability is violated. The system hence cannot achieve the desired goal. In this cases, feedback control, or usually known as close-loop control, should be used.

In a closed-loop control system, an input forcing function is determined in part by the system response. The measured outputs of a physical system are compared with the desired outputs. The difference between these two output initiates actions that will result in the actual response of the system to approach the desired response. This in turn drives the difference signal toward zero. The actions, which eliminate the system errors, are called a control algorithm. Typically the difference signal is processed by another physical system, which may be a compensator, a controller, or a filter for real-time control system applications. Normally a control algorithm also improves transient response characteristics, minimizes the effects of parameter variations, and gets rid of the effects of disturbance in-outs, hence enhances the overall performance of the system.

In our robotic marionette, a closed-loop control system can be constructed in several ways. By attached a rotary encoder to each motor, the string space outputs can be observed. This measured data are compared with the desired data. The errors are then fed into the control algorithm normally embedded in a controller. The algorithm will tell the controller how much voltage should be applied to the marionette system to achieve the desired motions. This is equivalent to joint space feedback control in manipulators. The block diagram of the closed-loop control of the marionette system using string space feedback is illustrated in Figure 5 and Figure 6.

Another way of feedback control for the marionette system is to install a vision system or something like that, to record the actual motions of the puppet. This approach is much more expensive and complicated than the former one. However the use of marionette motion feedback has several advantages compared with the string space closed-loop control. Firstly it can adapt quite well to the changes of work-environment, and even to inaccuracy kinematics. The closed-loop system using marionette motion feedback may also not depend much on inverse kinematics. Any disturbance from the string space to the marionette motion space can be eliminated (this is not possible for the former one, since that disturbance is not included in the feedback information). This control approach is equivalent to task space closed-loop control in manipulators. The block diagram of the closed-loop control of the marionette system using marionette motion feedback is illustrated in Figure 7.

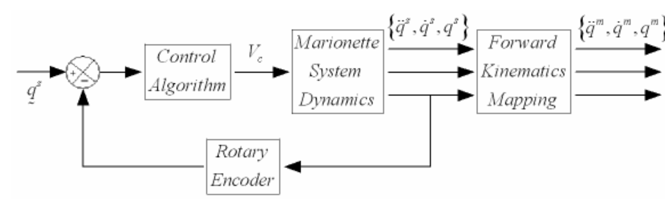

Figure 5 Closed-loop control with rotary encoder feedback

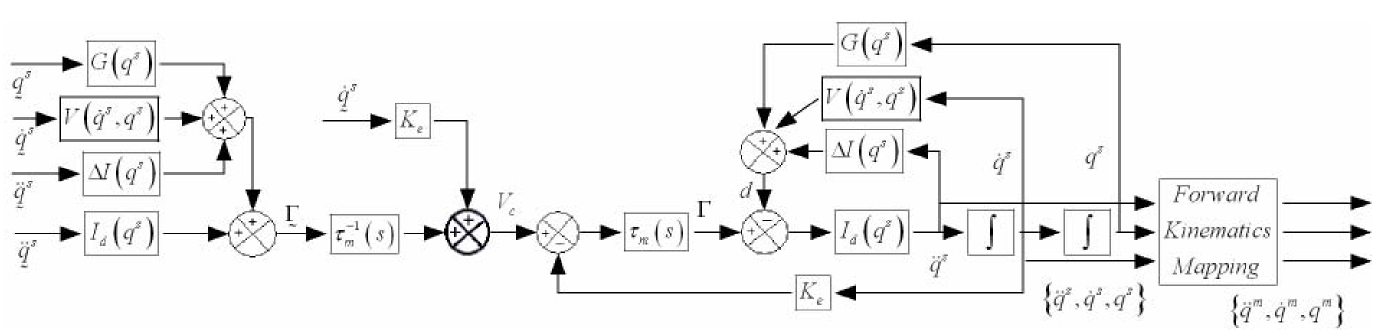

Figure 6 Detailed block diagram of closed-loop control with rotary feedback

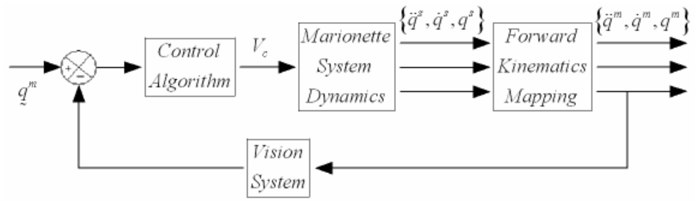

Figure 7 Closed-loop control with vision feedback (motion capture)

V. PARAMETER IDENTIFICATION

In the previous sections the complete dynamic model of the marionette system was derived based on Lagrange equation, with some discussions on feed-forward and feedback control. The model is written in state space form and represented by a set of dynamic parameters, such as matrix of inertial effects, matrix of viscous effects, matrix of gravitational effects, and so on. This section is dedicated to an identification scheme which can be used to determine those dynamic parameters.

Firstly the kinematic energy of a link in the marionette system can be written in the following form, including the linear and angular components

$$E_{ki} = \frac{1}{2} m_i . v_{ci}^t . v_{ci} + \frac{1}{2} \omega_i^t . \left\{ {}^0_f R_i \left({}^f I_i \right) {}^0_f R_i^t \right\} . \omega_i \qquad \text{(E10)}$$

The linear and angular velocities (or marionette motion space) of the link i[th] is related with the string space variables by the Jacobian matrix as shown in the expression below

$$\begin{pmatrix} v_{ci} \\ \omega_i \end{pmatrix}_{6\times1} = \begin{pmatrix} J_i^l \\ J_i^\omega \end{pmatrix}_{6\times n} \left(\dot{q}^s \right)_{n\times1} \qquad \text{(E11)}$$

In which, J_i^l and J_i^ω are linear and angular components of the matrix respectively

By converting the equation (E10) into string space using Jacobian matrix, we get

$$E_{ki} = \frac{1}{2} m_i . \left(J_i^l . \dot{q}^s \right)^T . \left(J_i^l . \dot{q}^s \right) + \frac{1}{2} \left(J_i^\omega . \dot{q}^s \right)^T . \left\{ {}^0_f R_i . \left({}^f I_i \right) . {}^0_f R_i^t \right\} . \left(J_i^\omega . \dot{q}^s \right)$$

Grouping the dynamic parameters gives

$$E_{ki} = \frac{1}{2} \left(\dot{q}^s \right)^T . \begin{bmatrix} m_i . \left(J_i^l \right)^T . \left(J_i^l \right) + \\ \frac{1}{2} \left(J_i^\omega \right)^T . \left\{ {}^0_f R_i \left({}^f I_i \right) {}^0_f R_i^t \right\} . \left(J_i^\omega \right) \end{bmatrix} . \dot{q}^s$$

The total kinetic energy of the system is known as the sum of kinetic energies of the individual links. This statement is described by the formula below

$$E_k = \sum_{i=1}^{n} E_{ki}$$

Hence

$$E_k = \frac{1}{2} \left(\dot{q}^s \right)^T . \left\{ \sum_{i=1}^{n} \begin{bmatrix} m_i . \left(J_i^l \right)^T . \left(J_i^l \right) + \\ \frac{1}{2} \left(J_i^\omega \right)^T . \left\{ {}^0_f R_i \left({}^f I_i \right) {}^0_f R_i^t \right\} . \left(J_i^\omega \right) \end{bmatrix} \right\} . \dot{q}^s$$

Compare this equation with kinetic energy equation, $E_k = \frac{1}{2} \left(\dot{q}^s \right)^T . I . \left(\dot{q}^s \right)$, we obtain the expression which allow to calculate the matrix of inertial effects

$$I = \sum_{i=1}^{n} \begin{bmatrix} m_i . \left(J_i^l \right)^T . \left(J_i^l \right) + \\ \frac{1}{2} \left(J_i^\omega \right)^T . \left\{ {}^0_f R_i \left({}^f I_i \right) {}^0_f R_i^t \right\} . \left(J_i^\omega \right) \end{bmatrix}$$

(E12)

By matrix multiplication, kinetic energy equation can be written in the form

$$E_k = \frac{1}{2} \sum_{i=1}^{n} \sum_{j=1}^{n} \left[I_{ij} \left(q^s \right) . \dot{q}_i^s . \dot{q}_j^s \right]$$

On the other hand the potential energy of a link can be written in the form

$$E_{pi} = -m_i . g . h_{ci}$$

The total potential energy of the system is determined by as the sum of potential energies of the individual links. This means

$$E_p = \sum_{i=1}^{i} E_{pi} = \sum_{i=1}^{i} \left(-m_i . g . h_{ci} \right)$$

The Lagrange equation can be expressed in term of kinematic and potential energies as following

$$\Gamma_i = \frac{d}{dt} \left(\frac{\partial E_k}{\partial \dot{q}_i^s} \right) - \left(\frac{\partial E_k}{\partial q_i^s} \right) + \left(\frac{\partial E_p}{\partial q_i^s} \right), \qquad for\ i = 1, 2, \ldots, n$$

(E13)

Now using some simple calculus of derivative, the terms in Lagrange equation (E13) are going to be determined. At first we have the derivative of kinetic energy with respect to the string velocity

$$\frac{\partial E_k}{\partial \dot{q}_i^s} = \sum_{j=1}^{n} \left[I_{ij} \left(q^s \right) . \dot{q}_j^s \right]$$

Taking differentiation of this equation with respect to time yields

$$\frac{d}{dt} \left(\frac{\partial E_k}{\partial \dot{q}_i^s} \right) = \sum_{j=1}^{n} \left[\dot{I}_{ij} \left(q^s \right) . \dot{q}_j^s + I_{ij} \left(q^s \right) . \ddot{q}_j^s \right] \qquad \text{(E14)}$$

According to chain rule of partial derivative

$$\dot{I}_{ij}\left(q^s\right)=\frac{\partial I_{ij}}{\partial q_1^s}.\dot{q}_1^s+\frac{\partial I_{ij}}{\partial q_2^s}.\dot{q}_2^s+\ldots+\frac{\partial I_{ij}}{\partial q_n^s}.\dot{q}_n^s$$

Or $$\dot{I}_{ij}\left(q^s\right)=\sum_{k=1}^{n}\left[\frac{\partial I_{ij}}{\partial q_k^s}.\dot{q}_k^s\right]$$

Plug this value into equation (E14), we have

$$\frac{d}{dt}\left(\frac{\partial E_k}{\partial \dot{q}_i^s}\right)=\sum_{j=1}^{n}\left[I_{ij}\left(q^s\right).\ddot{q}_j^s\right]+\sum_{j=1}^{n}\sum_{k=1}^{n}\left[\frac{\partial I_{ij}}{\partial q_k^s}.\dot{q}_k^s.\dot{q}_j^s\right] \quad \text{(E15)}$$

In addition, the derivative of kinetic energy with respect to the string position is

$$\frac{\partial E_k}{\partial q_i^s}=\frac{1}{2}\sum_{j=1}^{n}\sum_{k=1}^{n}\left[\frac{\partial I_{jk}}{\partial q_i^s}.\dot{q}_k^s.\dot{q}_j^s\right] \quad \text{(E16)}$$

And derivative of potential energy with respect to the string position is

$$\frac{\partial E_p}{\partial q_i^s}=\sum_{i=1}^{i}\left(-m_i.g.\frac{\partial h_{ci}}{\partial q_i^s}\right) \quad \text{(E17)}$$

Substitute the identified term in equations (E15), (E16) and (E17) in to the Lagrange equation (E13), we get the detailed form of inverse dynamic equation

$$\Gamma_i=\sum_{j=1}^{n}\left[I_{ij}\left(q^s\right).\ddot{q}_j^s\right]+$$
$$+\sum_{j=1}^{n}\left[\sum_{k=1}^{n}\left(\frac{\partial I_{ij}}{\partial q_k^s}-\frac{1}{2}\frac{\partial I_{jk}}{\partial q_i^s}\right).\dot{q}_k^s\right].\dot{q}_j^s-\sum_{i=1}^{i}\left(m_i.g.\frac{\partial h_{ci}}{\partial q_i^s}\right)$$

Thus the elements of matrix of centrifugal, Coriolis and viscous effects can be calculated by

$$V_{ij}\left(q^s,\dot{q}^s\right)=\sum_{k=1}^{n}\left(\frac{\partial I_{ij}}{\partial q_k^s}-\frac{1}{2}\frac{\partial I_{jk}}{\partial q_i^s}\right).\dot{q}_k^s \quad \text{(E18)}$$

And elements of the matrix of gravitational effects can be calculated from

$$G_i\left(q^s\right)=-\sum_{i=1}^{i}\left(m_i.g.\frac{\partial h_{ci}}{\partial q_i^s}\right) \quad \text{(E19)}$$

In summary, equations (E12) (E18) (E19) provide the necessary formulae to identify the important parameters which form the dynamic model of the robotic marionette system.

VI. CONCLUTION

Based on Lagrange equation and state-space representation systematic dynamic models were proposed in this paper, including an inverse dynamic model which computes the actuator torques needed for the robotic marionette to achieve desired motions, and a direct dynamic model which describes the string accelerations in term of the string positions, velocities and the toques at the actuators. We also studied dynamic model for open-loop and string-space closed-loop control of the robotic marionette. The control models can be considered a guide to design a motion controller for the marionette system. Then finally a strategy for identification of the model parameters was presented. Our dynamic models can be used as a mathematical tool for those who are working on string-driven robots in general, and especially robotic marionette projects.

For the next steps, we will implement the dynamic model on the ROMS III, to give it more accurate motion, less swinging, and thus better performance. The most challenging problem in designing the motion controller for the robotic marionette is how to get reliable motion feedbacks of the marionette, or in other words how to capture the motion of the marionette. As we know, there are several available technologies for capturing human motions. However marionettes have very small range of motion. Moreover anything attached to the puppet body will affect its performance. There are several possible solutions to this problem. A set of markers can be attached on the puppet so that their movements are captured by a set of cameras. Then the marker movements are converted to marionette motion using inverse kinematics. Alternatively we can also mount inertial/magnetic units [9] on the puppet to get the orientations of its links, and then convert the information into marionette motion. Once the feedback motion from the marionette is capture, the loop is closed and the control system design based on the dynamic model can be completed.

REFERENCES

[1] G. Hoffmann, "Teach-In of a Robot by Showing the Motion," *IEEE International Conference on Image Processing*, 1996, pp. 529–532.

[2] H. Hemami,"A Marionette-Based Strategy for Stable Movement", *IEEE Transaction on System, Man, and Cybernetics*, pp. 502–511, March/April 1993.

[3] K. Yamane, J.K. Hodgins, and H.B. Brown, "Controlling a marionette with human motion capture data," *Proc. IEEE Int. Conf. Robotics Automation*, pp. 3834–3841, 2003.

[4] E. Johnson, T. D. Murphey, "Dynamic Modeling and Motion Planning for Marionettes: Rigid Bodies Articulated by Massless Strings", *Proc. IEEE International Conference on Robotics and Automation*, pg. 330 – 335, 2007

[5] S. S. Xing, I-M Chen, "Design Expressive Behaviors for Robot Puppets", *Proc. 7th Int'l Conf. Control, Automation, Robotics, Vision*, Singapore, pp378-383, 2002.

[6] I-M Chen, S. S. Xing, R. Tay, S. H. Yeo, "Many strings attached: from conventional to robotic marionette manipulation", *IEEE Robotics & Automation Magazine*, Vol. 12, Iss. 1, pp. 59-74, March 2005.

[7] K. D. Nguyen, I-M Chen, S. H. Yeo, B. L. Duh, "Motion Control of a Robotic Puppet through a Hybrid Motion Capture Device", *Proc. IEEE International Conference on Automation Science and Engineering*, pg. 753-758, 2007.

[8] K. D. Nguyen, I-. M. Chen, T. C. Ng, "Planning Algorithms for S-curve Trajectories", IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM 2007), ETH Zürich, Switzerland, Sep. 2007.

[9] W. Dong, K. Y. Lim, F. Y. K. Goh, K. D. Nguyen, I.-M. Chen, S. H. Yeo, and H. B. L. Duh, "A Low-cost Motion Tracker and Its Error Analysis", *IEEE International Conference on Robotics and Automation*, Pasadena, California, 2008.