Modeling of the Master in the Bilateral Control of the Robin Heart Teleoperation System.

Vera Z. Pérez, Paweł Kostka, Arkadiusz Kandora, Zbigniew Nawrat, Luis B. Gutiérrez.

V. Z. Pérez, Department of Electronic Engineering, Universidad Pontificia Bolivariana, Medellín, Colombia. (e-mail: vera.perez@upb.edu.co); Bioengineering Center:
http://convena.upb.edu.co/~bioingenieria/index.html
P. Kostka, Foundation for Cardiac Surgery Development, Zabrze, Poland. (e-mail: pskostka@tlen.pl); URL: FCSD: http://frk.pl
A. Kandora, Foundation for Cardiac Surgery Development, Zabrze, Poland. (e-mail: kierrhs@tlen.pl); URL: FCSD: http://frk.pl
Z. Nawrat, Foundation for Cardiac Surgery Development, Zabrze, Poland. (e-mail: nawrat@frk.pl); URL: FCSD: http://frk.pl
L.B. Gutiérrez, is with Department of Electronic Engineering in Universidad Pontificia Bolivariana, Medellín, Colombia. (e-mail: lbgutie@ieee.org); URL: Grupo de Automática y diseńo:
http://amasd.upb.edu.co/.

Abstract

The Robin Heart system has been developed by the Foundation for Cardiac Surgery Development (FSCD) and conceived as a telesurgery system with two principal parts: a master system that is driven by the surgeon and a slave system that works directly on the patient interacting with the environment. The preceding studies present the results for the slave manipulator, including kinematic and dynamic analysis. This study focuses on the master, in order to make a contribution in the interaction of those two systems in the near future, traditionally working through bilateral control. Kinematic and dynamic analyses were performed creating a theoretical computational algorithm for dynamic modeling by Lagrange-Euler.

Index Terms

Bilateral control, Dynamic analysis, Kinematic analysis, Medical robotics, Modeling

Modelowanie narzędzia Master systemu teleoperacji Robin Heart pracującego w konfiguracji sterowania bilateralnego.

Streszczenie

System telemanipulatora chirurgicznego Robin Heart, złożony z modułu Master i ramienia wykonawczego Slave został zaprojektowany i wykonany w Fundacji Rozwoju Kardiochirurgii w Zabrzu. Niniejsza praca przedstawia analizę elementów kinematyki i dynamiki telemanipulatora w odniesieniu do narzędzia operatora Master. Stanowi to pierwszy krok dla całościowego modelu sterowania bilateralnego, którego powstanie planowane jest w najbliższej przyszłości. Dynamiczny model Lagrange'a-Eulera stanowił podstawę dla wyznaczenia przedstawionego algorytmu.

I. INTRODUCTION

TELEOPERATED robotic systems allow for carrying out tasks at a distance and have had diverse applications sectors in the last decades: from the industrial area to the nuclear and aerospace sector. These kinds of systems principally have the following components: (a) local zone, an operator and a master device; (b) remote zone, a slave device and its interaction with the environment; and (c) communications, the connection between local zone and remote zone [1].

In the medical area, the use of robotic teleoperated systems in minimal invasive surgery (MIS) is an application that is gaining more interest every day. The principal reasons for that are the advantages of precision, the elimination of the surgeon's hand trembling, the diminution of inpatient convalescence and rehabilitation, the reduction of pain, and aesthetic aid [2-5].

This technique had its origins in the early 1990s with two important events: (a) the creation of AESOP, a system to hold and drive the camera in a laparoscopic surgery, and (b) the development of "Green Telepresence surgery system" to assist soldiers injured in war by medical personnel out of conflict zones. Those events were the foundation to develop the most important systems for telesurgery at a worldwide level: Zeus® by Computer Motion and daVinci® by Intuitive Surgical, the only commercial system approved by the Food and Drug Administration (FDA) for use in Europe, USA and some Asian countries [6-8].

The principal obstacle for implementation of the da Vinci® Surgical System in more institutions around the world is the high cost. For that reason, since 2000 the Foundation for Cardiac Surgery Development (FCSD) is working on the Robin Heart project (RH). Today it is a functional teleoperated system for application in cardiac surgery procedures and with the possibility to expand its functionality to laparoscopic procedures. It has one arm to hold the laparoscopic camera and two other arms equipped with tools.

The Robin Heart project has the three fundamental components of telesurgical devices mentioned above. In this article the general characteristics of the

slave system and its control will be presented and the master system will be emphasized.
The paper is organized as follows: section II presents the description of the actual Robin Heart system; section III presents the kinematic and dynamic analysis of the master in RH with computed torque control; section IV presents results of the simulation and section V consists of the discussion and conclusions.

V. Z. Pérez is with the Department of Electronic Engineering, Universidad Pontificia Bolivariana, Medellín, Colombia. (e-mail: vera.perez@upb.edu.co); Bioengineering Center: http://convena.upb.edu.co/~bioingenieria/index.html
A. Kandora is with the Foundation for Cardiac Surgery Development, Zabrze, Poland. (e-mail: kierrhs@tlen.pl); URL: FCSD: http://frk.pl
L.B. Gutiérrez, is with Department of Electronic Engineering in Universidad Pontificia Bolivariana, Medellín, Colombia. (e-mail: lbgutie@ieee.org); URL: Grupo de Automática y diseño: http://amasd.upb.edu.co/.

II. DESCRIPTION OF ROBIN HEART

A. Slave system

This system is a 7 degree of freedom (DOF) parallel manipulator. From a mechanical point of view, it has two basic principles [9]: (a) Concept of "constant point mechanism", through spherical kinematics of the manipulator. In this case, the center of the robot is placed in the port, a small hole used to introduce the tools in laparoscopic surgery (b) Active kinematic, one of the methods to obtain stability of the port, where by the robot has two DOF more than necessary to move the tool and the body around the port is assumed to be an obstacle.
The kinematics and dynamics of the RH manipulator have been studied in previous research. Currently, the results of the kinematics have been implemented to create the control algorithms [10, 11]

B. Control system

Currently, the bases of the RH control system is being implemented on a Digital Signal Processor (DSP) [11-13], which: (a) translates commands in the master system to movements in the slave system; (b) provides adequate precision, accuracy and resolution to perform surgeries taking into account anatomical structures; (c) establishes scales to transform master/slave movements; (d) eliminates trembling.

C. Master system

Fig. 1 presents the RH master system, the device that the surgeon uses to send orders to the slave system. The actual system is a mechanical development in aluminum with 4 joints: 3 of them rotational and 1 of them prismatic. Each joint includes an encoder to detect the position of the master according to surgeon's hand movement.

Fig. 1. Master system in RH

With a model of the master system, it is possible to analyze its performance and its interactions with the environment responding to some mechanical conditions.

III. DEVELOPMENT OF THE MODEL

Although the developed model has 7 DOF, only four of them are considered because of the movement of the grasper does not affect the final position of the master.

A. Kinematic analysis

The kinematic analysis of the master system was done with help of the Denavit Hartenbergs' algorithm [14]. Fig. 2 shows the frame assignments.

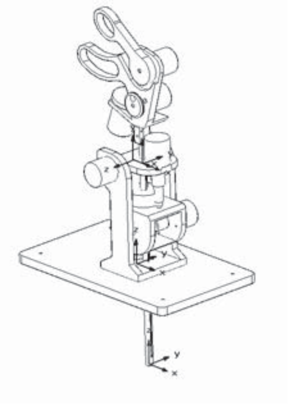

Fig 2. Frames assignment and axes for the kinematic analysis

See Fig. 3 for a two-dimensional diagram of the assignment.

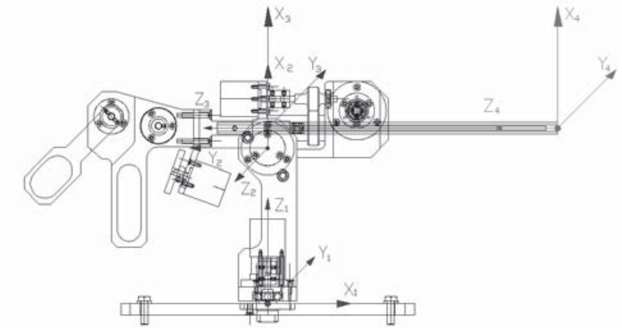

Fig. 3. View in two dimensions

Table 1 presents the Denavit Hardenberg's parameters for the RH master.

TABLE I

DENAVIT HARTENBERG´S PARAMETERS IN THE ROBIN HEART MASTER SYSTEM

i	θ_i	α_i	a_i	d_i
1	θ_1	$\pi/2$	0	d_1
2	θ_2	$-\pi/2$	l_1	0
3	θ_3	0	0	d_2

The mathematical equations are generated until the final position of the tool tip is found according to the values of the joints. The mathematic development and the notation will be according to Fu [14].

$$^{i-1}A_i = T(z,\theta_i)T(0,0,d_i)T(a_i,0,0)T(x,\alpha_i)$$

$$^0_4A = {}^0_1T\ {}^1_2T\ {}^2_3T\ {}^3_4T$$

$$^0_4A = \begin{bmatrix} c_1c_2c_3 - c_1s_2s_3 & -c_1c_2s_3 - c_1s_2c_3 & -s_1 & -s_1d_2 + c_1L_1 \\ s_2c_3 + c_2s_3 & -s_2s_3 + c_2c_3 & 0 & -d_1 \\ s_1c_2c_3 - s_1s_2s_3 & -s_1c_2s_3 - s_1s_2s_3 & c_1 & c_1d_2 + s_1L_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

B. Dynamic analysis

For the dynamic analysis of the system, the Lagrange- Euler method was utilized. It was necessary to use or calculate some important parameters of the actual model: mass, distance, center of mass and moments of inertia (see Table II).

The equations used in this item were based on Fu [14]. First, the kinematic analysis was performed on the manipulator, and later, the calculations of each one of the variables of the analysis by computed torque control were performed. The equation applied was:

$$\tau(t) = M(q(t))\ddot{q}(t) + h(q(t),\dot{q}(t)) + c(q(t)) \qquad (1)$$

Where τ(t)is a vector applied to the joints, q(t)is a vector of variables of arm joints, q(t) is a vector of velocities in the arm joints, q(t) is a vector of acceleration of variables of the joints q(t), M(q) is the mass matrix (a symmetric positive definite matrix), h(q,q) is a Coriolis' force and non-lineal centrifuge forces and c(q) a gravitational force vector.

It was necessary, then, to calculate the elements M (q), h (q,q), c (q) in expression (1). These calculations require some mechanical parameter values of the system, which are visualized in Table II.

The parameters were obtained as follows:

1) *Calculation of inertial matrix M(q):* The calculation of inertial matrix was done using the following equations:

$$M_{ik} = \sum_{j=máx(i,k)}^{n} Tr(U_{jk}J_jU_{ji}^T) \qquad (2)$$

with

$$i, k = 1,2,3,4$$

Where

$$U_{ij} = \left\{ \begin{array}{ll} {}^{0}A_{j-1} Q_j \, {}^{j-1}A_i & \text{for } j \leq i \\ 0 & \text{for } j > i \end{array} \right\} \quad (3)$$

${}^{0}A_{j-1}$: a transformation of frames matrix which present the relation between frame j-1 and the frame of the base.

Q_j : one matrix with two different values depending on the kind of joint. In the case of a rotational joint, the expression is (4).

$$Q_j = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (4)$$

And for a prismatic joint the expression is (5)

$$Q_j = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (5)$$

TABLE II. SIMULATION PARAMETERS

Parameter		Value	Unit
Mass	m1	0,369011	Kg
	m2	0,53126	
	m3	0,411071	
	m4	0,411071	
Distance	L1	0,01625	m
	d1	0,13	
	d2	0,252	
Moments of inertia	Ixx1	0,00322	Kg*m^2
	Iyy1	0,002892	
	Izz1	0,000543	
	Ixx2	0,012832	
	Iyy2	0,014305	
	Izz2	0,001983	
	Ixx3	0,007852	
	Iyy3	0,011788	
	Izz3	0,004092	
	Ixx4	0,007852	
	Iyy4	0,011788	
	Izz4	0,004092	

Center of gravity	Sx1	0,009166	m
	Sy1	0,006537	
	Sz1	0,0682586	
	Sx2	0,0418053	
	Sy2	0,0052137	
	Sz2	0,1528359	
	Sx3	0,0809951	
	Sy3	0,0075497	
	Sz3	0,1351744	
	Sx4	0,0809951	
	Sy4	0,0075497	
	Sz4	0,1351744	

${}^{j-1}A_i$: the matrix of transformation to relate the frame i with frame j-1. This matrix of general transformation can be seen in expression (6)

$$
{}^{i-1}A_i = \begin{bmatrix} \cos\theta_i & -\cos\alpha_i sen\theta_i & sen\alpha_i sen\theta_i & a_i \cos\theta_i \\ sen\theta_i & \cos\alpha_i \cos\theta_i & -sen\alpha_i \cos\theta_i & a_i sen\theta_i \\ 0 & sen\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (6)
$$

And J_j is one matrix defined in function of inertia tensor. I_{ij}

$$
J_j = \begin{bmatrix} \frac{-I_{xx}+I_{yy}+I_{zz}}{2} & I_{xy} & I_{xz} & m_i\bar{x}_i \\ I_{xy} & \frac{I_{xx}-I_{yy}+I_{zz}}{2} & I_{yz} & m_i\bar{y}_i \\ I_{xz} & I_{yz} & \frac{I_{xx}+I_{yy}-I_{zz}}{2} & m_i\bar{z}_i \\ m_i\bar{x}_i & m_i\bar{y}_i & m_i\bar{z}_i & m_i \end{bmatrix} \qquad (7)
$$

The assignments of values in table II were calculated with help of the software Solid Edge®. The frame 0 or base was chosen as a reference in the calculations. Joint 1, 2 and 3 can be seen in figures 4, 5 and 6 respectively.

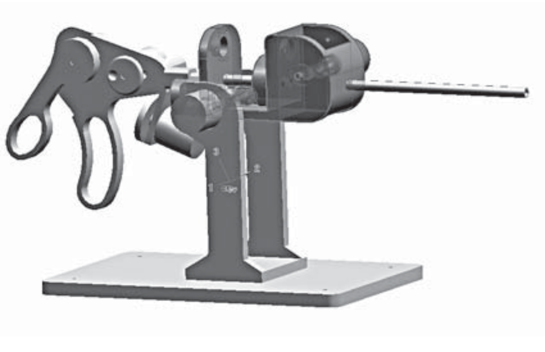

Fig. 4. Link 1

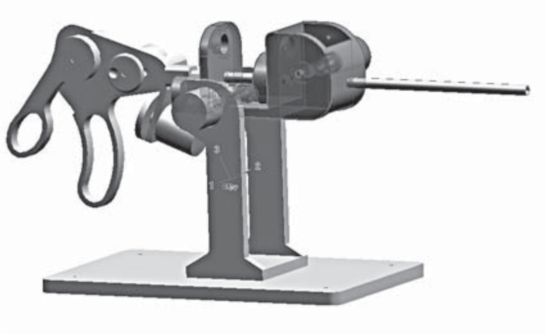

Fig. 5. Link 2

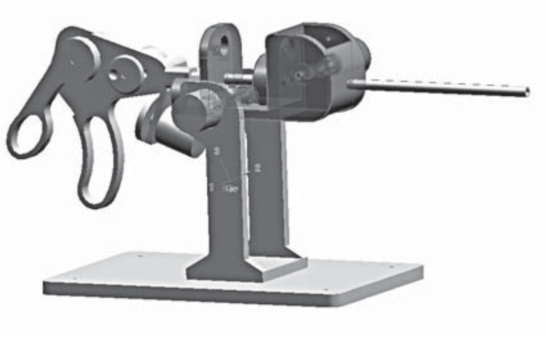

Fig. 6. Link 3 and 4

2) Calculation of Coriolis and centrifugal forces h (q,q):

$$h_i = \sum_{k=1}^{n} \sum_{m=1}^{n} h_{ikm} \dot{q}_k \dot{q}_m \text{ with } i = 1,2,\ldots,n \qquad (8)$$

Where:

$$h_{ikm} = \sum_{j=\text{máx}(i,k,m)}^{n} Tr(U_{jkm} J_j U_{ji}^T) \text{ with } i,k,m = 1,2,3,4 \qquad (9)$$

Where the expression U_{jkm} are the effects between joints:

$$U_{ijk} = \begin{Bmatrix} {}^0A_{j-1} Q_j {}^{j-1}A_{k-1} Q_k {}^{k-1}A_i & i \geq k \geq j \\ {}^0A_{k-1} Q_k {}^{k-1}A_{j-1} Q_j {}^{j-1}A_i & i \geq j \geq k \\ 0 & i < j \quad \text{ó} \quad i < k \end{Bmatrix} \qquad (10)$$

3) Calculation of gravitational force vector c(q): The expression used is (11)

$$c_i = \sum_{j=i}^{n} (-m_j G U_{ji} {}^j\bar{r}_j) \text{ with } i = 1,2,\ldots,n \qquad (11)$$

Where:

m_j is the mass of each joint in Kg. These are the first four lines in table II.

$G = (g_x, g_y, g_z, 0)$ is one row vector of gravity expressed in the coordinated system of the base. In the case of the RH robot, $G = (0,0,-|g|,0)$ according to assignment of frames, where g is the gravitational constant ($g = 9.8062 m/s^2$).

U_{ji} is the definition presented in expression (3).

${}^j r_j$ is the center of mass vector for each joint.

IV. RESULTS AND DISCUSSION

All the joints acted in a similar way. The results are presented in figure 7, 8 and 9.

The solid line in figure 7 and 8 shows the desired trajectory for each joint in the master tool robot and the dotted line is the real trajectory after applying controlled torque.

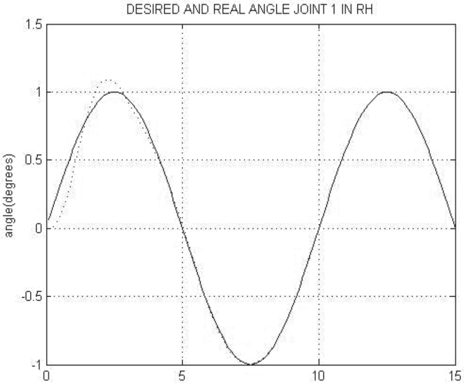

Fig. 7. Desired and real performance of joint 1

In this case, the system took about 6 seconds and moved exactly like the desired trajectory in each joint. This time is optimum according to the application of the system and the requirements of the user.

The error in the control system is the difference between the desired and the real angle in the previous graphics for each joint. In these kinds of applications, the performance of the system with the control is asymptotically stable and the state stable is zero. The error of the system is shown in Fig. 8.

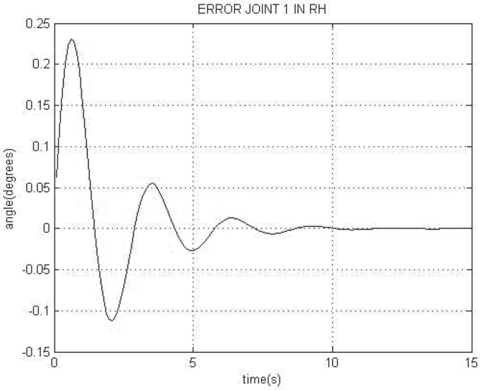

Fig. 8. Error in joint 1

The system is completely stabilized after 10 seconds.
Finally, the torque in each joint is presented in figure 9.

It is important to create a model of the master tool for analyzing the actual condition of the system and present some considerations about its design for futures constructions:

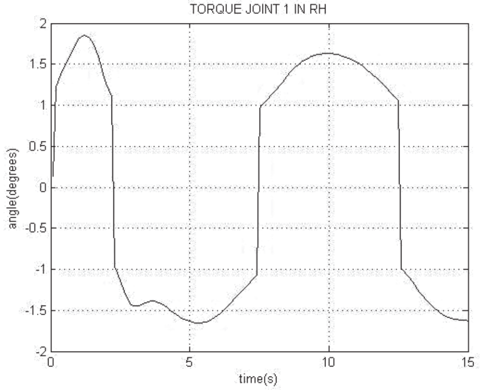

Fig. 9. Torque in joint 1

- It is possible to verify the performance when the material is substituted. The results will be different with respect to the initial results because if the material changes, the density changes and as a consequence the mass changes. Since the inertial matrix depends on mass, that parameter varies too. An approximate result of equation (1) can be obtained, but the model has the advantage of permitting input of exact new parameters and visualizing new graphics.

- If one part of the mechanical system changes, it is possible to know the new parameters with help of the blueprints of the system, the new mass of each link and the input to the model, thus verifying the new performance.
- The initial model considers a presumed friction force. Nevertheless, it is possible to input the real friction, according to the materials of the surfaces in contact and in this way choose combinations of materials for better performance.
- A system with 4 DOF was analyzed, but it is possible to have more DOF as is the case with the master tool in the FCSD. The performance will be the same even if the analysis considers the 3 DOF excluded from the model, since these do not represent changes in the mechanical parameters of the system.
- This dynamic analysis and simulation is only possible when we do not assume one passive system. In this case we are supposing each joint of the master tool are moved by direct current (DC) motors and the analysis includes some characteristics of this kind of motor. In reality it is the operator who manipulates the system. However, with this consideration it is possible to obtain results of the simulation with constant inputs, because in the case of the operator, these forces are variable and are not easy to measure.
- One additional analysis of this model can include human movements like actuators in the system, using data in the review of the state of the art. Nevertheless, it is necessary create approximate model taking into account muscles actions, reaction forces, etc. and analyzing the results.

V. CONCLUSIONS

Kinematics and dynamics of the Robin Heart master tool have been presented. The analysis of the kinematics was done with help of Denavit Hartenbergs' algorithm. For the dynamic analysis of the system, the Lagrange-Euler method was used calculating some parameters with help of the software Solid Edge®. A simulation including an analysis by computed torque control was performed and as a result, an asymptotically stable system and a stable state zero were found.

The simulation corresponds to the master block in the telesurgical system RH, taking into account the forces applied by the surgeon and the forces originated in the slave.

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