Modelling and Identification of STAUBLI RX-60 Robot

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***Abstract*— This paper deals with the modelling and identification of an industrial Staubli RX-60 robot. A Lagrange-Euler method is used to derive the dynamic equations of the robot. The dynamic model introduced here was obtained with the distinct parameters. In this paper, a least squares estimation for determining parameters of a dynamic Staubli RX-60 Robot model based on experiments was used. The robot was moved with respect to many experiments formed. At the end of the movement, data such as the position and velocity was taken from the robot. Moreover, the acceleration was taken from SIMI Motion with a three cameras system and torque was measured from the loadcell (FTC-L50) sensor during the robot experiments. The inertial parameters of the robot were estimated according to these data. The estimation values were verified experimentally. The experimental results show that the estimated inertial parameters predict robot dynamics well. The errors of the torque estimation were also computed and they are between 0.0171 Nm and 0.1136 Nm.**

I. INTRODUCTION

Determination of inertial parameters of robot manipulators is often required for advanced control algorithms. The dynamic model, either in the form in inertial parameters or in the form in the minimal set of inertial parameters, is then used to determine this set of parameters experimentally. That is, for various trajectory of the robot, corresponding values of positions, velocities, torques and accelerations of the joints are measured. Based on these experimental values, the inertial parameters are then estimated by some kind of "best fit'.

To use a dynamic model for control of a robotic system, one must be sure that the model closely matches the real dynamics. To enable a close match, the structure of the model should be capable of describing the relevant aspects of the physics and accurate values for the model parameters are needed. So far, a number of theoretical and experimental studies on estimating model parameters have been reported. Each exploits the well-known property that a model of the robot dynamics can be represented linearly in a minimum set of identifiable parameters.

Most robot manipulators are not equipped with joint torques/force sensors. Thus, estimates of joint torques and forces must be used. A typical estimate is from the motor current [1, 2]. The most efficient way to obtain accurate values of the unknown model parameters may be experimental parameter identification using the assembled robot. The problem of obtaining these parameters by means of experimental estimation has been addressed by many authors. The identification of the robot as experimental estimation must be revealed. A general overview of experimental robot identification using linear least squares techniques can be found in the textbooks of [3] and [4].

In this paper, a least squares (LS) estimation method was applied to obtain an accurate estimation of the parameters. The least square method optimizes the root-mean square (rms) residual error of the model under the assumption that the measurement errors are negligible. However, in [5] it has been observed that there are problems with the parameter estimates of the least square method. One of the problem is the sensitivity to measurement noise. To overcome this problem, one can generate so-called "exciting trajectories and/or use data filtering. By using such "input data improvement", a lot of excellent parameter estimations using the least square method has been obtained [6-8].

The minimum inertial parameters are defined as the minimum set of constant inertial parameters that do not contain the zero element and are sufficient to calculate the dynamic model of the robot. They can be obtained from the classical inertial parameters by eliminating those that have no effect on the dynamic model. A model must be presented for determining these parameters. The dynamical equations of a manipulator consist of a number of mathematical equations that define the behavior of the manipulator dynamics. This is a second order non-linear differentiate equation. A robot arm dynamic model can be obtained from physical laws known such as Newton and Lagrangian mechanics [9-10]. There are a lot of methods for obtaining the equations of the robot arm dynamics. They are the approaches such as Lagrange-Euler (L-E), Recursive Lagrange (R-L), Newton-Euler (N-E) and Generalized D'Alambert (G-D) principle [11]. The most used methods are the approaches to L-E and N-E. In this process, an approach to L-E which has a well planned structure and is more simple and more systematic than an approach to N-E is used in order to obtain the robot dynamic model.

In this paper, the dynamic model of the three first links of a six-axis Staubli RX-60 robot was obtained. The minimum inertial parameters of the robot could be attainable by using the

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given model. The LS error method was used for determining inertial parameters of a dynamical robot model based on experiments. The values of the parameters were obtained by this method. These values which were obtained from experimental results were tested.

II. DYNAMIC MODEL OF THE ROBOT

The dynamical analysis of the robot arm investigates a relation between the joint torques/forces applied by the actuators and the position, velocity and acceleration of the robot arm with respect to the time. Robot manipulators have complex nonlinear dynamics that might make accurate and robust control difficult. Fortunately, robots are in the class of Lagrangian dynamical systems, so that they have several extremely nice physical properties that make their control straightforward.

A. D-H Parameters of RX-60 Robot

The Denavit-Hartenberg (or D-H) technique has become the standard method in robotics for describing the forward kinematics of a manipulator. Essentially, by careful placement of a series of coordinate frames fixed in each link, the D-H technique reduces the forward kinematics problem to that of combining a series of straightforward consecutive link-to-link transformations from the base to the end effector frame.

Table 1 shows the D-H parameters of Staubli RX-60. According to the D-H convention, D-H parameters of RX-60 Robot are represented as:

α_{i-1} : Link twist;

a_{i-1} : Link length;

d_i : Link offset;

θ_i : Joint angle;

TABLE I. *LINK PARAMETERS FOR STAUBLI RX-60 ROBOT*

I	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	d_1	θ_1
2	-90	0	0	θ_2
3	0	a_2	d_3	θ_3
4	90	0	d_4	θ_4
5	-90	0	0	θ_5
6	90	0	0	θ_6

Where: a_2 =0.29 m, d_1 =0.237 m, d_3 =0.049 m, d_4 =0.31 m [13].

This manipulator, which is called Staubli RX-60 Robot of Figure 1, consists of an RRR arm and three degrees of freedom wrist. The first step is to locate and label the joint axes as shown.

This is completely arbitrary and the robot arm is the zero configuration of the manipulator, that is, the position of the manipulator when $\theta_1, \theta_2, \theta_3, \theta_4, \theta_5$ and $\theta_6 = 0$.

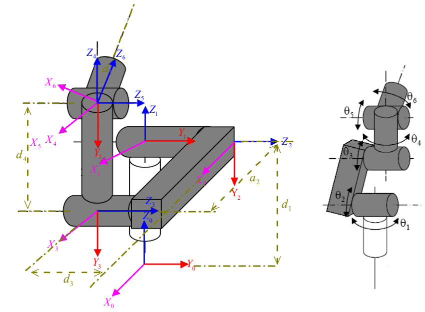


Figure 1. D-H coordinate frame assignment for Staubli RX-60 Robot.

B. Obtaining Dynamic Model

The dynamics of robot manipulators with rigid links can be written as

$$\tau = D(q)\ddot{q} + C(q,\dot{q}) + G(q) \tag{1}$$

where $D(q)\ddot{q}$ is the inertia matrix, $C(q,\dot{q})$ is the coriolis/centripetal matrix, $G(q)$ is the gravity vector, and τ is the control input torque. The joint variable q is an n-vector containing the joint angles for revolute joints and lengths for prismatic joints.

Using θ as the vector of joint angles, the dynamics of the three first links of a six-axis Staubli RX-60 robot can be modelled by:

$$\begin{pmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \end{pmatrix} = \begin{pmatrix} d_{11} & d_{12} & d_{13} \\ d_{21} & d_{22} & d_{23} \\ d_{31} & d_{32} & d_{33} \end{pmatrix} \begin{pmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \\ \ddot{\theta}_3 \end{pmatrix} + \begin{pmatrix} c_1(\theta,\dot{\theta}) \\ c_2(\theta,\dot{\theta}) \\ c_3(\theta,\dot{\theta}) \end{pmatrix} + \begin{pmatrix} g_1(\theta) \\ g_2(\theta) \\ g_3(\theta) \end{pmatrix} \tag{2}$$

where θ, $\dot{\theta}$ and $\ddot{\theta}$ respectively are joint position, velocities and accelerations.

The torque equation of the three first links of a six-axis Staubli RX-60 robot can be computed by:

$$\tau_1 = \left[c^2\theta_2 \left(a_2^2 m_3 + m_2 a_{2_C}^2 + B_{yy_2} \right) + A_{xx_2} s^2\theta_2 + B_{yy_3} c^2(\theta_2+\theta_3) \right.$$

$$-c\theta_2 \left(-2m_3 a_2 s(\theta_2+\theta_3) d_{4_C} + 2F_2 s\theta_2 \right) - 2F_3 c(\theta_2+\theta_3) \mathrm{s}(\theta_2+\theta_3)$$

$$\left. + \mathrm{s}^2(\theta_2+\theta_3)\left(m_3 d_{4_C}^2 + A_{xx_3} \right) + m_3 d_3^2 + C_{ZZ_1} \right] \ddot{\theta}_1 + \left[c\theta_2 D_2 \right.$$

$$+ s\theta_2 \left(E_2 + a_2 d_3 m_3 \right) + c(\theta_2+\theta_3)\left(D_3 - d_3 m_3 d_{4_C} \right)$$

$$\left. + E_3\, \mathrm{s}(\theta_2+\theta_3) \right] \ddot{\theta}_2 + \left[c(\theta_2+\theta_3)\left(D_3 - d_3 m_3 d_{4_C} \right) + E_3\, \mathrm{s}(\theta_2+\theta_3) \right] \ddot{\theta}_3$$

$$+ \left[-s(2\theta_2)\left(a_2^2 m_3 + m_2 a_{2_C}^2 + B_{yy_2} \right) + s(2\theta_2) A_{xx_2} - s(2(\theta_2+\theta_3)) B_{yy_3} \right.$$

$$+2m_3a_2d_{4_C}c(\theta_2+(\theta_2+\theta_3))-2F_2c(2\theta_2)$$

$$-2F_3c(2(\theta_2+\theta_3))+s(2(\theta_2+\theta_3))\left(m_3d_{4_C}^2+A_{xx_3}\right)\Big]\dot{\theta}_2\dot{\theta}_1$$

$$+\Big[-s\theta_2D_2+c\theta_2\left(E_2+a_2d_3m_3\right)-s(\theta_2+\theta_3)\left(D_3-d_3m_3d_{4_C}\right)$$

$$+E_3c(\theta_2+\theta_3)\Big]\dot{\theta}_2^2+2\Big[-s(\theta_2+\theta_3)\left(D_3-d_3m_3d_{4_C}\right)$$

$$+E_3c(\theta_2+\theta_3)\Big]\dot{\theta}_2\dot{\theta}_3+\Big[-s(2(\theta_2+\theta_3))B_{yy_3}$$

$$-c\theta_2c(\theta_2+\theta_3)(-2m_3a_2d_{4_C})-2F_3c(2(\theta_2+\theta_3))$$

$$+s(2(\theta_2+\theta_3))\left(m_3d_{4_C}^2+A_{xx_3}\right)\Big]\dot{\theta}_3\dot{\theta}_1$$

$$+\Big[-s(\theta_2+\theta_3)\left(D_3-d_3m_3d_{4_C}\right)+E_3c(\theta_2+\theta_3)\Big]\dot{\theta}_3^2$$

$$\tau_2=\Big[c\theta_2D_2+s\theta_2\left(E_2+a_2d_3m_3\right)+c(\theta_2+\theta_3)\left(D_3-d_3m_3d_{4_C}\right)$$

$$+E_3\,\mathrm{s}(\theta_2+\theta_3)\Big]\ddot{\theta}_1+\Big[C_{ZZ_2}+C_{ZZ_3}+m_2a_{2C}^2+m_3\left(a_2^2+d_{4_C}^2\right)$$

$$+2\,\mathrm{s}\theta_3a_2d_{4_C}m_3\Big]\ddot{\theta}_2+\Big[m_3d_{4_C}^2-a_2m_3s\theta_3d_{4_C}+C_{ZZ_3}\Big]\ddot{\theta}_3$$

$$-\frac{1}{2}\Big[s(2\theta_2)\left(A_{xx_2}-\left(a_2^2m_3+m_2a_{2C}^2+B_{yy_2}\right)\right)$$

$$+s(2(\theta_2+\theta_3))\left(\left(m_3d_{4_C}^2+A_{xx_3}\right)-B_{yy_3}\right)$$

$$+2m_3a_2d_{4_C}c(\theta_2+(\theta_2+\theta_3))-2F_2c(2\theta_2)-2F_3c(2(\theta_2+\theta_3))\Big]\dot{\theta}_1^2$$

$$+\Big[2c\theta_3a_2m_3d_{4_C}\Big]\dot{\theta}_3\dot{\theta}_2+\Big[-c\theta_3a_2m_3d_{4_C}\Big]\dot{\theta}_3^2$$

$$+g_0m_3d_{4_c}s(\theta_2+\theta_3)+g_0m_2a_{2_c}c\theta_2+g_0a_2m_3c\theta_2$$

$$\tau_3=\Big[c(\theta_2+\theta_3)\left(D_3-d_3m_3d_{4_C}\right)+E_3\,\mathrm{s}(\theta_2+\theta_3)\Big]\ddot{\theta}_1$$

$$+\Big[m_3d_{4_C}^2-s\theta_3a_2m_3d_{4_C}+C_{ZZ_3}\Big]\ddot{\theta}_2+\Big[m_3d_{4_C}^2+C_{ZZ_3}\Big]\ddot{\theta}_3$$

$$-\frac{1}{2}\Big[-s(2(\theta_2+\theta_3))B_{yy_3}-c\theta_2c(\theta_2+\theta_3)(-2m_3a_2d_{4_C})$$

$$-2F_3c(2(\theta_2+\theta_3))+s(2(\theta_2+\theta_3))\left(m_3d_{4_C}^2+A_{xx_3}\right)\Big]\dot{\theta}_1^2$$

$$-\frac{1}{2}\Big[2c\theta_3a_2m_3d_{4_C}\Big]\dot{\theta}_2^2+g_0m_3d_{4_C}s(\theta_2+\theta_3)$$

The terms in equations above will be explained in chapter 3

III. IDENTIFYING THE PARAMETER OF RX-60 ROBOT

Advanced robot control algorithms usually rely on model-based control techniques in order to accomplish a desired level of accuracy and compliance. Thus, accurate model identification is a highly important topic for advanced robot control, and many modern robotics applications rely on it (e.g., as in haptic robotic devices, robotic surgery and the safe application of compliant assistive robots in human environments).

Equation (2) can also be expressed linearly in terms of the physical parameters of the system. The non-linear robot terms are *linear in the parameters* of mass and friction so that one can write

$$Y(\theta,\dot{\theta},\ddot{\theta})\alpha=\tau \tag{3}$$

where $Y(\theta,\dot{\theta},\ddot{\theta})$ is a matrix of known measured joint values $\theta,\dot{\theta}$ and $\ddot{\theta}$, and α is a vector of unknown parameters of the robot. Generally, it includes masses, link dimensions, and even constants of friction.

For RX-60 Robot, the elements involved in (3) are computed. First vector α including the constant terms is expressed.

$$\begin{aligned}\alpha=[&\alpha_1\ \alpha_2\ \alpha_3\ \alpha_4\ \alpha_5\ \alpha_6\ \alpha_7\ \alpha_8\\ &\alpha_9\ \alpha_{10}\ \alpha_{11}\ \alpha_{12}\ \alpha_{13}\ \alpha_{14}\ \alpha_{15}\ \alpha_{16}]^T\end{aligned} \tag{4}$$

These elements involved in (4) are either known constant parameters or unknown parameters of RX-60. The physical meaning of the parameters α_1 ,,, α_{16} is given in Table 2.

TABLE II. *PHYSICAL MEANING OF PARAMETERS*

Parameter	Meaning	Unit
α_1	$a_2^2m_3+m_2a_{2_c}^2+B_{yy_2}$	$kg.m^2$
α_2	A_{xx_2}	$kg.m^2$
α_3	B_{yy_3}	$kg.m^2$
α_4	$2m_3a_2d_{4_c}$	$kg.m^2$
α_5	$-F_2$	$kg.m^2$
α_6	$-F_3$	$kg.m^2$
α_7	$m_3d_{4_c}^2+A_{xx_3}$	$kg.m^2$
α_8	$m_3d_3^2+C_{ZZ_1}$	$kg.m^2$
α_9	D_2	$kg.m^2$
α_{10}	$E_2+a_2d_3m_3$	$kg.m^2$
α_{11}	$D_3-d_3m_3d_{4_c}$	$kg.m^2$

α_{12}	E_3	$kg.m^2$
α_{13}	$C_{ZZ_2} - B_{yy_2}$	$kg.m^2$
α_{14}	$C_{ZZ_3} - A_{xx_3}$	$kg.m^2$
α_{15}	$g_0 m_2 a_{2_c} + g_0 m_3 a_2$	$kg.m^2/s^2$
α_{16}	$g_0 m_3 d_{4_c}$	$kg.m^2/s^2$

Variables as stated above are in Table 2 where *m* is link mass; *a* and *d* are link length and link offset (Denavit-Hartenberg parameters) respectively; d_{4_c} ve a_{2_c} are coordinates of link's centers of gravity in the frame 4 and 2; *A, B, C* are link's moments of inertia matrix; *E, F, D* are link's products of inertia matrix; g_o is the value of gravity.For Staubli RX-60 Robot dynamics the regressor matrix $Y(\theta,\dot{\theta},\ddot{\theta})$ is given by

$$Y = \begin{pmatrix} y_{11} & y_{12} & y_{13} & \cdot & \cdot & \cdot & y_{116} \\ y_{21} & y_{22} & y_{23} & \cdot & \cdot & \cdot & y_{216} \\ y_{31} & y_{32} & y_{33} & \cdot & \cdot & \cdot & y_{316} \end{pmatrix}_{3x16} \tag{5}$$

A. Estimation of Inertial Parameters

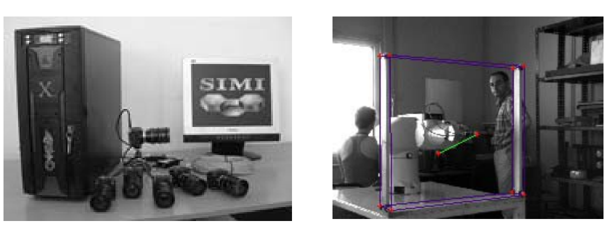
The vector can generally be estimated from (3) using the least squares method as

$$\alpha = (Y^T Y)^{-1} Y^T \tau \tag{6}$$

If the input τ sufficiently excites the manipulator dynamics, then the least squares estimate of α will be existence. There are several criteria evaluating sufficiency of excitation. The usual one is the condition number of the information matrix $(Y^T Y)^{-1} Y^T$, defined as the ratio between maximal and minimal singular values of $(Y^T Y)^{-1} Y^T$. If this number is closer to one, the excitation is considered to be better for a reliable estimation of α. In addition, the least squares method may not be applied directly when $(Y^T Y)^{-1}$ does not exist [12].

IV. Experimental Results

For identification of the robot parameter, the positions and velocities of the joints were obtained from incremental encoders during motion of the robot along a given trajectory. In each experiment, torque at end effector was measured from FTC-L50 sensor. In Figure 2, three cameras in SIMI Motion system with 300 Hz were used for measuring the accelerations of the joints. The data is obtained from the data acquisition card at the sampling rate of 1 kHz.



(a) (b)

Figure 2. SIMI Motion System and an Acceleration Experiment Setup.

A. Experimental Procedure

Vector α has included the constant parameters known such as the coordinates of center of gravity, link's length and link mass. By writing the values of these parameters in (4), vector α can be simplified to

$$\alpha = \big[0.5597 + B_{yy_2},\ A_{xx_2},\ B_{yy_3},\ 0.1255,\ -F_2,\ -F_3,\ 0.0130 + A_{xx_3},\ 0.0087 + C_{ZZ_1},\ D_2,\ 0.0512 + E_2,\ D_3 - 0.0106,\ E_3,\ C_{ZZ_2} - B_{yy_2},\ C_{ZZ_3} - A_{xx_3},\ 24.7750,\ 2.1197\big]^T$$

The above α is used in determining inertial parameters of each joint. The programs were composed for implementation of (6) by using Matlab/Simulink software.

Here, in Matlab the trajectory equations have been designed by composing the programs which can make the writing task such as a circle, an ellipse, a bulb, an ellipsoid, a helix and a desired trajectory. A total of the six experiments was made with respect to these trajectories. These trajectories were applied on the RX-60 robot. The desired data was obtained from the robot during tracking these trajectories.

The table below clearly demonstrates all values of the parameters in vector α that were obtained at the end of a total of the six experiments shown above, but values of α_4, α_{15} and α_{16} were calculated from data sheet parameters. All of the columns show the value of the parameters, and the rows show the parameters in the vector α in Table 3.

TABLE III. *Values of Vector α*

α	Exp.1	Exp.2	Exp.3	Exp.4	Exp.5	Exp.6
α_1	2.6412	2.5935	2.8242	3.1333	2.4098	2.9768
α_2	1.3659	1.3143	1.3853	1.1982	1.3311	1.3950
α_3	1.1893	1.3150	1.2248	1.1562	1.2269	1.3639
α_4	0.1255	0.1255	0.1255	0.1255	0.1255	0.1255
α_5	-0.2632	0.8591	0.1570	0.1535	0.8992	-0.5470
α_6	-0.3487	-0.2446	-0.3995	-0.1067	-0.4057	-0.1595
α_7	0.1588	0.1581	0.2375	0.1460	0.1398	0.2698
α_8	5.9423	5.5719	4.9693	5.5327	4.6663	5.0116
α_9	-0.0390	0.0508	-0.0052	-0.0386	-0.0139	-0.0507
α_{10}	-0.0048	-0.0075	-0.0010	-0.0001	-0.0006	-0.0041
α_{11}	-0.0018	-0.0013	-0.0021	-0.0051	-0.0030	-0.0011
α_{12}	-0.0055	-0.0042	-0.0021	-0.0028	-0.0027	-0.0028
α_{13}	2.6416	3.0584	2.6880	2.8690	2.4255	2.8106
α_{14}	0.4379	0.4961	0.4205	0.4317	0.3134	0.3944
α_{15}	24.7750	24.7750	24.7750	24.7750	24.7750	24.7750
α_{16}	2.1197	2.1197	2.1197	2.1197	2.1197	2.1197

At the end of the six experiments, the *mean* and *standard deviation* of all α below were obtained as shown the following table

TABLE IV. THE MEANS AND STANDARD DEVIATIONS IN VECTOR α

α	**Means**	**Standard Deviations**
α_1	2.7631	0.2664
α_2	1.3316	0.0724
α_3	1.2460	0.0784
α_4	0.1255	0
α_5	0.2098	0.5830
α_6	-0.2775	0.1269
α_7	0.1850	0.0546
α_8	5.2824	0.4760
α_9	-0.0161	0.0370
α_{10}	-0.0030	0.0029
α_{11}	-0.0024	0.0015
α_{12}	-0.0034	0.0013
α_{13}	2.7488	0.2163
α_{14}	0.4157	0.0603
α_{15}	24.7750	0
α_{16}	2.1197	0

As the goal in this here is to determine the values of inertial parameters of joints, vector α is determined as the following

$$\alpha = [2.7631 \;\; 1.3316 \;\; 1.2460 \;\; 0.1255 \;\; 0.2098 \;\; -0.2775 \;\; 0.1850 \;\; 5.2824 \;\; -0.0161 \;\; -0.0030 \;\; -0.0024 \;\; -0.0034 \;\; 2.7488 \;\; 0.4157 \;\; 24.7750 \;\; 2.1197]$$

Table 5 shows the values of the elements of inertia matrix with the moment and products of inertia of link remained by eliminating the parameters that have no effect on the dynamic model in vector α .

TABLE V. STAUBLI RX-60 ROBOT MINIMUM PARAMETER VALUES

Joint	A_{xx}	B_{yy}	C_{zz}	D	E	F
1	0	0	5.2737	0	0	0
2	1.3316	2.2034	4.9522	-0.0161	-0.0542	-0.2098
3	0.1720	1.2460	0.5877	0.0082	-0.0034	0.2775

B. Estimation Result Verification

To verify the estimation results, a totally different motion was applied to the robot. The estimated α is used to predict the torques measured from FTC-L50 sensor during motion.

Finally, the predicted torque can be calculated as $Y(\theta,\dot{\theta},\ddot{\theta})\alpha = \tau$. The velocity is filtered for maintaining a good least square estimation after getting the required transformations [14]. So, the start and the end of the trajectory have been filtered in order to ensure a smooth motion and to reduce the transients.

In the end, the required filters are applied by using the final obtained vector α and thus, the predicted torques match well those from sensor measurements as shown in Figure 4 a-c.

$$\theta_1(t) = c.r.\sin\left(\frac{t\pi}{4}\right) \quad (7)$$

$$\theta_2(t) = -c.r.\cos\left(\frac{t\pi}{4}\right) \quad (8)$$

$$\theta_3(t) = ones\left(size(\beta)\right).\cos\left(\frac{t\pi}{4}\right) \quad (9)$$

Where c=0.6, r is the value which changes between -1.2 and -0.85, β is the value which changes between 255 and 360. Robot moves according to the trajectories of joints above as shown in Figure 3.

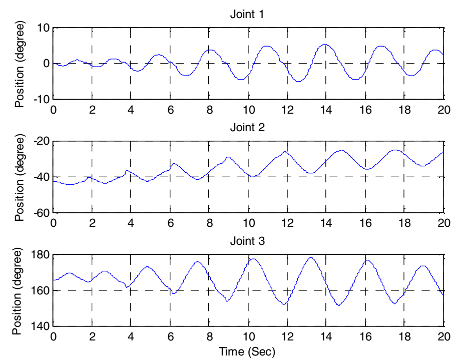
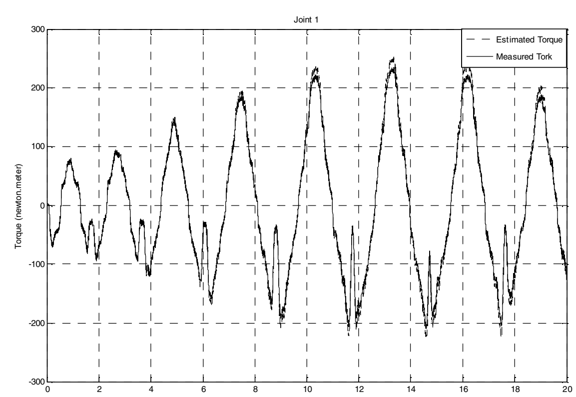


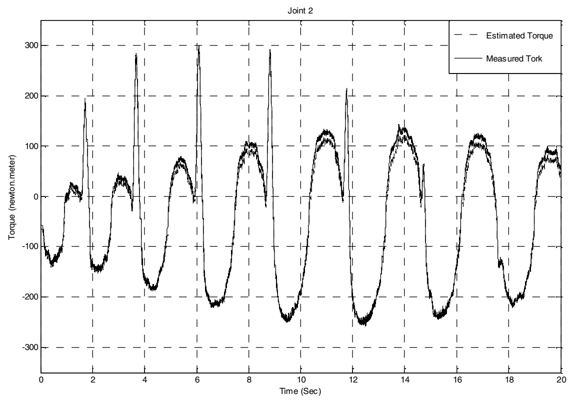
Figure 3. Joint 1 (θ_1), Joint 2 (θ_2) and Joint 3 (θ_3) During Verification Motion.

The data is recorded form the incremental encoders at the sampling of 1 kHz during manipulator motion. Time of the movement in the experiment was equal to 20 sec. After these data have been collected, the estimation of the torque can be reached by analyzing these data.

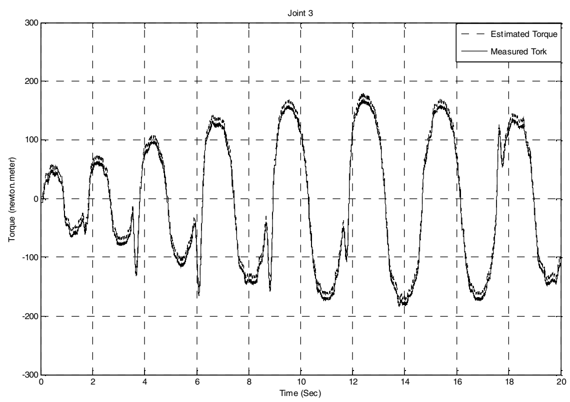
In Figure 4, the measured and simulated joint torques have been plotted. The graph of torques shows the relation between the estimated torques and measured torques.



(a)



(b)



(c)

Figure 4. Estimated and Measured Torques.

The objective in here is to reveal the accuracy of the values of the unknown parameters obtained by means of experimental identification using dedicated experiments. The results in Figure 4 have been indicating that there is a good agreement between the measurement and the estimation.

To verify the estimation results, a totally three different experiments was made. Table 6 shows the errors having occurred in the result of all three experiments. These estimation errors were obtained by dividing sum of the squares of the differences between the actual observed and the computed values into the number of data.

TABLE VI. ESTIMATION ERRORS

Experiment	Joint 1	Joint 2	Joint 3
1	0.0256	0.0171	0.0252
2	0.0043	0.1136	0.0036
3	0.0176	0.082	0.0091

V. CONCLUSIONS

In this paper, the modeling and identification of Staubli RX-60 robot have been presented. A least squares estimation method has been used to estimate the inertial parameters of the robot.

The proposed method has been tested experimentally, and the results show that the estimated inertial parameters predict robot dynamics well. Moreover, the error of the estimation occurred between 0.008 and 0.112 by using estimation result verification at the end of the estimation. It was shown that LS method was able to find such parameters of the robot's model. Experimental results validate the effectiveness of the proposed LS method.

It can be concluded that accurate identification result can be obtained from a different sufficiently exciting identification trajectory. Furthermore, the obtained parameter values result in an accurate dynamic robot model. The accuracy depends on the measurement accuracy of the encoders. Further work is required on systematic analysis of the estimation accuracy. Other important remaining issues are the identifiably of inertial parameters and the selection of efficient exciting trajectories.

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