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Identifiability of the Dynamic Parameters of a Class of Parallel Robots in the Presence of Measurement Noise and Modeling Discrepancy

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Advanced model based control schemes and the solution of the direct dynamic problem requires accurate knowledge of the dynamic parameters of robotic systems, mainly the inertial properties of the links and friction parameters at the kinematic joints. Only a subset of the dynamic parameters of a robot, known as "base parameters", can be identified. When parameter identification is performed experimentally, not all the aspects of the robot can be modeled in detail. Moreover, there is noise in measurement variables. These sources of error lead to the fact that not all the base parameters can be properly identified. Therefore, in this paper, the identifiability of the dynamic parameters of a 3 DOF RPS parallel robot, in the presence of noise in measurement and discrepancy in modeling, is addressed. The analysis is carried out by means of a simulated robot and over an actual parallel 3-RPS manipulator.

Keyword: Parallel Robots, Dynamic Parameter Identification, Base Parameters, Dynamic Modeling.

INTRODUCTION

Accurate knowledge of the dynamic parameters of robotic systems (the inertial properties of links and friction parameters at the kinematic joints) is essential not only for some advanced control schemes based on inverse dynamics but also for dynamic simulation tools when solving the direct dynamic problem.

Generally, the information provided by robot manufacturers regarding dynamic parameters is limited and even nonexistent (i.e., friction parameters). Therefore, it is necessary to develop efficient procedures for their measurement. The direct measurement of these properties is not practical since it would imply disassembling the robot. On the other hand, it could be done by using CAD models. Nevertheless, this method has the disadvantage that some parts cannot be modeled in full detail and parameters that depend on operational conditions, like friction, cannot be determined. For these reasons, parameter identification has turned out to be a widely accepted technique for the determination of dynamic parameters.

In the identification process, dynamic parameters are estimated by fitting the response of the dynamic model of the robot to the measured data (generalized coordinates and external forces). It must be mentioned that experimental parameter identification procedures have been developed and applied to serial robots; however, the number of papers on parallel robots is significantly smaller.

Identification procedures can be classified into two main groups: indirect and direct approaches. On the one hand, indirect procedures act sequentially in several steps. In each step, parameters of a different nature (basically friction and some inertial terms) are identified by means of specifically designed experiments. On the other hand, in the direct approach, all the parameters are identified at the same stage. The main steps of the direct approach can be summarized as follows: A dynamic linear model is established with respect to the dynamic parameters to be identified. This linear model is reduced to a canonical system to obtain the so-called “base parameters”, which can be achieved symbolically (Gautier & Khalil, 1990) or numerically (Gautier, 1991). In order to reduce the sensitivity of the system to the noise signal, optimal trajectories have to be found (“exciting trajectories”) (Gautier & Khalil, 1992; Otani & Kakizaki, 1993; Swevers *et al.*, 1997a; Swevers *et al.*, 1997b). Finally the dynamic system, under its reduced matrix form, is solved for the base parameters using the Least Squares Method (LSM). A comparison between the two approaches applied to a serial robot can be found (Benimeli *et al.*, 2006).

For parallel robots the indirect approach is not straightforward, even though procedures allowing independent identification of friction characteristics and gravity terms have been proposed (Abdellatif *et al.*, 2007; Grotjahn *et al.*, 2004). The direct approach for parallel robots has been applied (Farhat *et al.*, 2008; Guegan *et al.*, 2003; Renaud *et al.*, 1993). Due to the fact that the direct approach allows parameter identification in one single experiment, this approach is used in this paper for dynamic parameter identification.

When a direct parameter identification process is performed experimentally, two sources of error become apparent. On the one hand, not all the aspects of the robot can be modeled in detail (discrepancies in modeling). On the other hand, there is noise in measurements. These errors lead to the fact that not all the base parameters can be properly identified. The objective of this paper is twofold. The first one is to emphasize that in the presence of these sources of error, some of the base parameters cannot be properly identified. The second one is to evaluate the identifiability of the dynamic parameters for a class of parallel robots in the presence of noise measurements and when some aspects of modeling are omitted. The analysis is carried out by means of a simulated robot and over an actual parallel 3 DOF RPS manipulator built at the Polytechnic University of Valencia. It is important to mention that to accomplish the objectives of the research, a simulated robot was built such that its dynamic behavior was as close as possible to the actual one.

This paper is organized as follows. In the next section, the dynamic linear model with respect to the dynamic parameters of a parallel robot is developed. Afterwards, models used for the parameter identification of a 3-RPS are presented. Then, simulations and experiments used for the purpose of the study are described. The last part of the paper presents the results of the identifiability of the dynamic parameters for an identification process applied over both the simulated robot and actual robot. Finally, the main conclusions and future work are presented.

DYNAMIC

From the Gibbs-Appell equations of motion, the rigid body dynamic model for a serial robot can be written in linear form with respect to the dynamic parameters (Mata *et al.*, 2005) as follows,

$$K\left(\vec{q},\dot{\vec{q}},\ddot{\vec{q}}\right)\cdot\vec{\Phi}_{rb}=\vec{\tau} \quad (1)$$

where $\vec{\tau}$ is the vector of generalized forces and $\vec{\Phi}_{rb}$ is a vector of the regrouped inertia parameters. K can be denoted as a single configuration observation matrix, this matrix depending on the generalized kinematic variables (the Denavit-Hartenberg modified convention has been considered in order to model the system). The vector of dynamic parameters $\vec{\Phi}_{rb}$ contains the elements of; the inertia tensor $\begin{bmatrix} I_{xx_i} & I_{xy_i} & I_{xz_i} & I_{yy_i} & I_{yz_i} & I_{zz_i} \end{bmatrix}^T$ of body (*i*) around, the mass m_i and the first mass moment with respect to its local reference frame $\begin{bmatrix} mx_i & my_i & mz_i \end{bmatrix}^T$.

For parallel robots, the dynamic model can be obtained by making a cut at one or more joints so that the manipulator can be dealt with as various open-chain mechanical systems with a tree structure. By doing so, equation (1) can be applied for the several open chain mechanical systems obtained after the cut. However, the constraint equations representing the union at the cut joints should be fulfilled. These equations have the following form,

$$f_i(q_1, q_2, ..., q_n) = 0 \quad i = 1, 2, ..., m \tag{2}$$

where $(q_1, q_2, ..., q_n)$ are the generalized coordinates and *m* is the number of independent constraint equations. The degree of freedom (n_{DOF}) of the system is obviously (*n-m*). Taking the first and second derivatives of the previous equation with respect to time, acceleration constraint equations can be written as follows,

$$\mathbf{A}(\vec{q}) \cdot \ddot{\vec{q}} - \vec{b}(\vec{q}, \dot{\vec{q}}) = \vec{0} \tag{3}$$

where **A** is the Jacobian matrix of the constraint equations with respect to the generalized coordinates, $\vec{b}$ is a vector that contains all the terms that remain after removing all the acceleration dependent terms from the acceleration constraint equations. Regrouping the terms of the matrix **A**, according to the coordinated partition, in independent/dependent generalized accelerations produces,

$$\begin{bmatrix} \mathbf{A}_i & \mathbf{A}_e \end{bmatrix} \begin{bmatrix} \ddot{\vec{q}}_i \\ \ddot{\vec{q}}_e \end{bmatrix} = \vec{b} \tag{4}$$

where, $\mathbf{A}_i$ and $\mathbf{A}_e$ are obtained when the above mentioned coordinated partition is applied to the Jacobian matrix of the constraint equations.

Similarly, regrouping equation (1) but this time according to the independent and dependent generalized coordinates, produces

$$\begin{aligned} \mathbf{K}_i \cdot \vec{\Phi}_{rb} &= \vec{\tau}_i \\ \mathbf{K}_e \cdot \vec{\Phi}_{rb} &= \vec{\tau}_e \end{aligned} \tag{5}$$

Subindices i and e refer to independent and dependent generalized coordinates respectively.

Starting from equation (4) and (5), it can be proved (Udwadia & Kalaba, 1998) that the dynamic equation for a parallel robot in parameter linear form can be written as follows,

$$\left[\mathbf{K}_{\mathrm{i}} - \mathbf{X}^{\mathrm{T}} \cdot \mathbf{K}_{\mathrm{e}}\right] \cdot \vec{\Phi}_{\mathrm{rb}} = \vec{\tau}_{\mathrm{i}} - \mathbf{X}^{\mathrm{T}} \cdot \vec{\tau}_{\mathrm{e}} \tag{6}$$

where $\mathbf{X} = \mathbf{A}_{\mathrm{e}}^{-1} \cdot \mathbf{A}_{\mathrm{i}}$.

If the dependent generalized forces correspond to passive joints, then they do not exert any external force. Hence, equation (6) is reduced to,

$$\left[\mathbf{K}_{\mathrm{i}} - \mathbf{X}^{\mathrm{T}} \cdot \mathbf{K}_{\mathrm{e}}\right] \cdot \vec{\Phi}_{\mathrm{rb}} = \vec{\tau}_{\mathrm{i}} \tag{7}$$

The observation matrix for a given trajectory can be found by appending this equation for all the configurations (n_{pts}) of the corresponding trajectory. This gives,

$$\begin{bmatrix} \left[\mathbf{K}_{\mathrm{i}} - \mathbf{X}^{\mathrm{T}} \cdot \mathbf{K}_{\mathrm{e}}\right]_1 \\ \left[\mathbf{K}_{\mathrm{i}} - \mathbf{X}^{\mathrm{T}} \cdot \mathbf{K}_{\mathrm{e}}\right]_2 \\ \vdots \\ \left[\mathbf{K}_{\mathrm{i}} - \mathbf{X}^{\mathrm{T}} \cdot \mathbf{K}_{\mathrm{e}}\right]_{\mathrm{n_{pts}}} \end{bmatrix} \cdot \vec{\Phi}_{\mathrm{rb}} = \begin{bmatrix} \left[\vec{\tau}_{\mathrm{i}}\right]_1 \\ \left[\vec{\tau}_{\mathrm{i}}\right]_2 \\ \vdots \\ \left[\vec{\tau}_{\mathrm{i}}\right]_{\mathrm{n_{pts}}} \end{bmatrix} \tag{8}$$

The left-hand side of this equation is the observation matrix for a given trajectory ($\mathbf{W}_{\mathrm{rb}}$) and the right-hand side is the corresponding applied forces ($\vec{\tau}$). In compact matrix form,

$$\mathbf{W}_{\mathrm{rb}}\left(\vec{\mathrm{q}}, \dot{\vec{\mathrm{q}}}, \ddot{\vec{\mathrm{q}}}\right) \cdot \vec{\Phi}_{\mathrm{rb}} = \vec{\tau} \tag{9}$$

Friction Model

Several friction models have been proposed in the literature (Olsson *et al.*, 1998). In this paper we limit ourselves to linear ones, so in this manner a linear method for solving overdetermined system (i. e., LSM), can be applied. Equation (10) represents a classical friction model used for dynamic parameter identification.

$$\tau_{fi} = \begin{cases} F_c^{+} \cdot \mathrm{sign}(\dot{q}_i) + F_v \dot{q}_i & \text{if} \quad q_i \geq 0 \\ F_c^{-} \cdot \mathrm{sign}(\dot{q}_i) + F_v \dot{q}_i & \text{if} \quad q_i < 0 \end{cases} \tag{10}$$

where F_c^{+} and F_c^{-} stand for the Coulomb friction coefficients for positive and negative velocity respectively. F_v is the viscous friction coefficient. This model is asymmetrical with respect to the Coulomb friction coefficients. If F_c^{+} and F_c^{-} are assumed to be equal, the model reduces to a symmetrical one. Applying the friction model to all joints and for all the configurations (n_{pts}) produces,

$$\mathbf{W}_f(\dot{\vec{q}}) \cdot \vec{\Phi}_f = \vec{\tau}_f \tag{11}$$

Actuator Dynamics

In some cases, a considerable part of the actuator torque is consumed by accelerating or decelerating its rotor inertia (J_r) and its driving system (for instance, a ball screw-driven, J_s). Then the rotor and the driving system inertia have to be considered. The corresponding equations for the actuator of the i-th joint has the form,

$$\tau_{ri} = (J_{ri} + J_s) \cdot \ddot{q}_i \tag{12}$$

The actuator dynamic for all joints and for all the configurations (n_{pts}) can be expressed in matrix form as,

$$\mathbf{W}_r(\ddot{\vec{q}}) \cdot \vec{\Phi}_r = \vec{\tau}_r \tag{13}$$

Complete Robot Model

Combining equations (8), (10), and (13) the complete dynamic robot model can be expressed as follows,

$$\begin{bmatrix} \mathbf{W}_{rb} & \mathbf{W}_{f} & \mathbf{W}_{r} \end{bmatrix} \begin{bmatrix} \vec{\Phi}_{rb} \\ \vec{\Phi}_{f} \\ \vec{\Phi}_{r} \end{bmatrix} = \vec{\tau} \quad (14)$$

DYNAMIC MODELS OF A 3-RPS PARALLEL ROBOT

The 3-RPS parallel robot considered in this paper depicted in Figure (1). It consists of a fixed base and a moving platform interconnected by three RPS limbs. The axes of rotation of the revolute joints are assumed to share the same plane as the base. Spherical joints are kinematically modeled as 3 successive revolute joints with the corresponding rotation axes passing through the center of the spherical joint. The linear motion of each prismatic joint is achieved through a ball screw driven by a DC motor.

This parallel robot consists of 7 bodies and 3 actuators, each one containing two bodies and the platform, with each link having 10 inertial parameters. Then for a trajectory of n_{pts} configurations, the linear rigid body model is appended in the following matrix form,

$$\mathbf{W}_{(n_{DOF} \bullet n_{pts}) \times (70 + n_{fric} + n_J)} \cdot \vec{\Phi}_{(70 + n_{fric} + n_J) \times 1} = \vec{\tau}_{(n_{DOF} \bullet n_{pts}) \times 1} \quad (15)$$

In addition to the rigid body parameters, if it is considered an asymmetrical friction model at prismatic joints, equation (10), 9 parameters have to be identified. The complete model, considering actuator dynamics, adds 2 parameters for each actuator. Then a model with a total of 85 parameters is obtained. The complete model does not describe the dynamic behavior of the mechanical system independently. Therefore, it is necessary to find the base parameter model. This is carried out by using a numerical procedure based on Singular Value Decomposition (SVD) (Gautier & Khalil, 1990). The reduced model has the form,

$$\mathbf{W}_{red}\left(\vec{q}, \dot{\vec{q}}, \ddot{\vec{q}}\right) \cdot \vec{\Phi}_{base} = \vec{\tau} \quad (16)$$

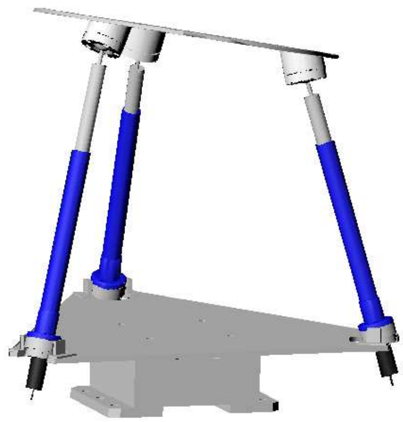

Figure 1. 3-RPS parallel robot ADAMS

Figure 2. Actual 3-RPS parallel robot

where $\mathbf{W}_{red}$ is the reduced matrix after applying SVD procedures and $\vec{\Phi}_{base}$ is the base parameters vector. This vector is formed by 25 parameters associated with the rigid body parameters. Rigid body base parameters are listed in Table 1. All friction parameters are linearly independent. The parameters that describe actuator dynamics are in linear combination, which leads to 1 parameter per actuator $\left(J_r + J_S\right)$. The reduced model has a total of 37 parameters. This model is called Model 1 here.

If the geometry of robot parts is taken into account, some rigid body base parameters have zero values or values close to it. Consider for instance the 3-RPS robot (Figure. (1)) where the links connected to the base have a cylindrical geometry. It can be supposed with a degree of certainty that the gravity center of these links lies on an axis parallel to the actuator movement. In this case, the corresponding axis of the local reference system attached to the body is in (y) direction, thus the parameter related to the (x) position of the gravity center can be expected to have values close to zero. The same assumption is applied to links connected to the moving platform. Therefore, parameters 1, 4, 14, 18, 20, 24 from Table 1 can be removed. Moreover, it is possible to consider the form of the platform, which is circular and flat, thus parameters 7, 8, 10, 13 can be removed. This reduced model is highlighted by (*) in Table 1 and is called Model 2 here. For parameter identification this model includes a symmetric friction model and the actuator inertia.

Another simplification can be applied if the parallel robot symmetry is considered. In Table 1 the rigid body base parameters of this case is highlighted by (**).This new reduced model, called Model 3, has 9 rigid body base parameters. It is important to mention that the columns of the observation matrix, associated with base parameters that consider the symmetric, have to be added in order to develop a model which properly describes the dynamic behavior of the robot. Similar to Model 2, only symmetric friction models were used and the actuator inertia was also included. The number of parameters of Model 3 is 18.

Table 1. Rigid body base parameters for Model 1, Model 2 (*) and Model 3 (**).

No	Base Parameters	No	Base Parameters
1	$mx(1)$	14	$mx(4)$
2	$my(1)$*, **	15	$my(4)$*
3	$I_{zz}(1)+I_{yy}(2)$*, **	16	$I_{yy}(5)+ I_{zz}(4)$*
4	$mx(2)$	17	$m(5)-2.531my(3)+m(3)+m(2)$*,** ,†
5	$mz(2)$* , **	18	$mx(5)$
6	$I_{xx}(3)-0.3952my(3)$* , **	19	$mz(5)$*
7	$I_{xy}(3)+0.2282my(3)$	20	$mx(6)$
8	$I_{xz}(3)$		
9	$I_{yy}(3)+0.3952my(3)-0.2082(m(3)+m(2))$ * , **	21	$my(6)$*
10	$I_{yz}(3)$	22	$I_{yy}(7)+ I_{zz}(6)$*
11	$I_{zz}(3)-0.2082 (m(3)+m(2))$* , **	23	$m(7)+2.531my(3)$* , **,†
12	$mx(3)+0.5774my(3) - 0.4563(m(3)+m(2))$ * , **,†	24	$mx(7)$
13	$mz(3)$	25	$mz(7)$*

SIMULATIONS AND EXPERIMENTS

The identifiability of the dynamic parameters of a 3-RPS parallel robot was addressed considering a simulated robot. The results from this analysis were then used for the parameter identification of an actual parallel robot designed in the Polytechnic University of Valencia. The simulated robot was made making use of the ADAMS dynamic simulation software. Moreover, it was built in such a way that its dynamic behavior was as close as possible to the actual one. In order to accomplish that, a CAD model was developed with similar dimensions to the actual robot, see Figure (1) and (2). Simulated friction models take advantage of parameters obtained from a previously performed parameter identification (Farhat et al., 2008). The values of rotor and screw inertias were selected considering their values as those of a cylinder with dimensions similar to the screws. The final values of the parameters were found, after several attempts, adjusting the simulated robot to the actual one. Figure (3) depicts a comparison of the dynamic behavior of the simulated robot with the actual one from 3 different trajectories.

For simulations and experiments, three different exciting trajectories were considered. All the trajectories were found by optimizing a parameterized trajectory based on finite Fourier series (Swevers et al., 1997a). This method has many advantages and has been widely implemented. The final condition numbers of the trajectories were 571, 595 and 601. Parameter identification was carried out by means of the Least Squares Method (LSM). The dynamic model of this robot, trajectory optimization and identification procedures were developed in FORTRAN programming language with the aid of the NAG Math Library.

The description of the procedures employed for evaluating the identifiability of the dynamic parameters of the simulated robot can be summarized as follows,

- Noise addition to the generalized forces and independent generalized coordinates and their time derivates. This in order to evaluate how well the dynamic parameter in the presence of noise can be identified.
- For identification when discrepancy in modeling occurs, three scenarios are evaluated. Case 1: Friction in prismatic joints with a nonlinear tendency and the identification model considering only linear models. Case 2: Friction at rotational joints is neglected in the identification model, and Case 3: The actuator dynamics are neglected in the identification model.

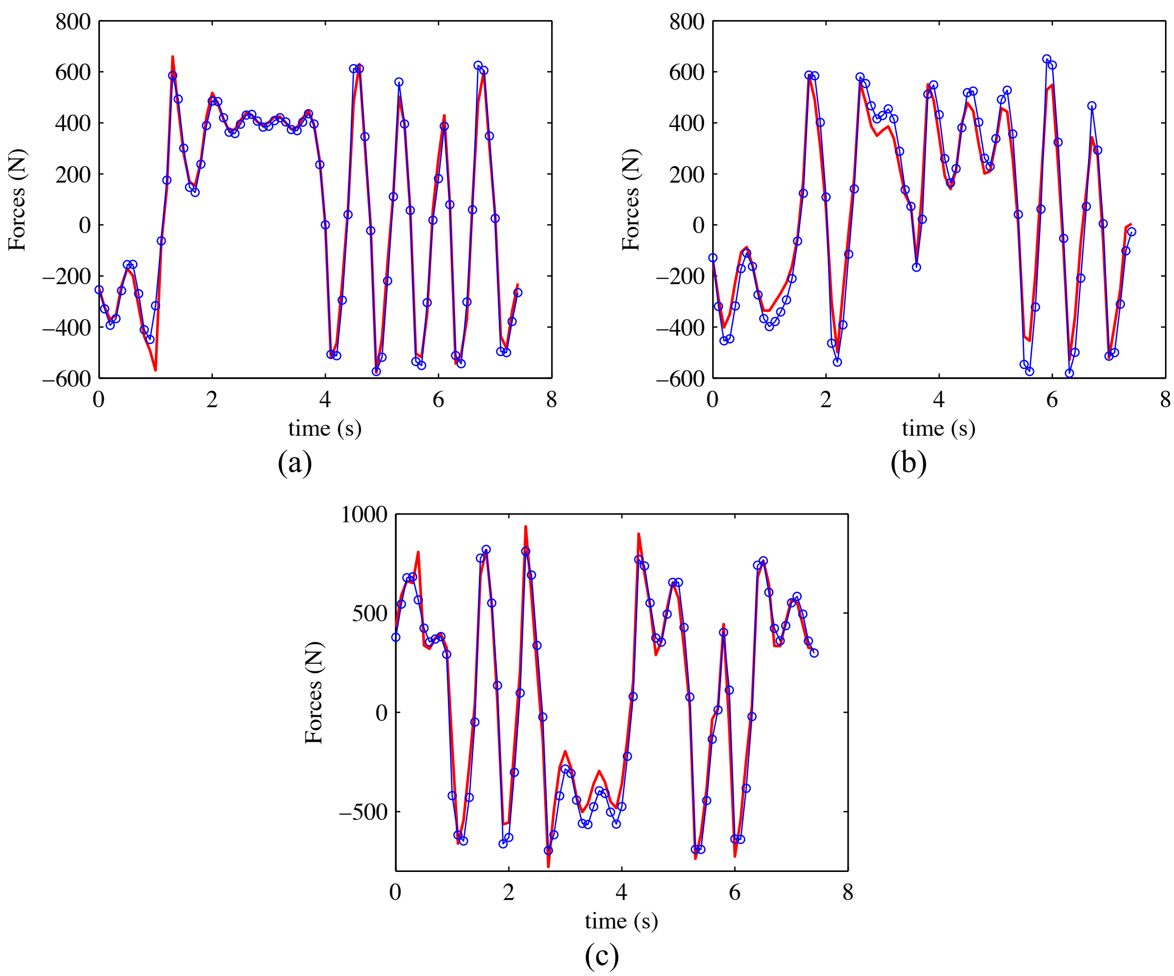

Figure 3. Forces from Actual Robot (-red) and Forces from Simulated Robot (–o blue), (a)Trajectory 595, (b)Trajectory 571 and (c)Trajectory 601

For all the cases mentioned above, the study of which parameters can be properly identified was established upon analyzing the relative standard deviation (σ_{pi}) of each parameter, as has been proposed (Khalil & Dombre, 2002), and considering physical feasibility (Yoshida & Khalil, 2000). On the one hand, the minimum value of σ_{pi} was taken as reference. Thus, parameters with values of σ_{pi} below 10 times the reference were considered properly identified. On the other hand, the physical feasibility was considered by evaluating the values of 1) base parameters 3, 16 y 22 of Tables (1) and 2) friction parameters, these parameters must be positive. After evaluating the simulated robot, conclusions were used for parameter identification of the actual parallel robot.

APPLICATION TO THE SIMULATED MODEL

Noise in Measurements

When a direct parameter identification process is performed experimentally, two sources of error become apparent. On the one hand, not all the aspects of the robot can be modeled in detail (discrepancies in modeling). On the other hand, noise is present in measurements. These errors lead to the fact that not all the base parameters can be properly identified. This apparently occurs when the independent contribution of some parameters to the generalized forces is smaller than the measurement noise or the modeling discrepancies. In order to analyze the noise influence on the identification process, random Gaussian noise was added to the kinematic variables and force values obtained from the simulated parallel robot previously described. For the kinematic variables a zero mean value was used and the standard deviation was varied between zero to four percent of the variable values. This due to the fact that when errors in positions were greater than 4 % the nonlinear problem associated to the direct kinematics problem could not be found a solution. The standard deviation for the forces was varied between zero to five percent of its values. The data for the identification process is found by using the following equation,

$$\begin{aligned} q_i^* &= q_i + \delta \\ \tau_i^* &= \tau_i + \eta \end{aligned} \tag{17}$$

where δ and η are the noise added to the independent generalized coordinates q_i and τ_i. q_i^* and τ_i^* are the disturbed values.

Models 1, 2 and 3 were used for studying which parameters were properly identified. The validation of each model was checked using the relative absolute error (ε_{RA}) defined as,

$$\varepsilon_{RA} = \frac{\sum_i \left| \tau_{idnt_i} - \tau_i^* \right|}{\sum_i \left| \tau_i^* - \overline{\tau^*} \right|} \tag{18}$$

where, τ^* and τ_{idnt} are the actual applied force and those calculated using the dynamic model applying identified dynamic parameters, and $\overline{\tau^*}$ is the average of τ^*.

In addition, the average relative error of the identified parameter relative to the exact parameter (ε_{AV}) was also used,

$$\varepsilon_{AV} = \frac{1}{n_p} \sum \left| \frac{\Phi_i - \widehat{\Phi}_i}{\Phi_i} \right| \tag{19}$$

where , Φ_i was the exact values of the parameter and $\widehat{\Phi}_i$ was the identified parameters.

Figure (4) depicts ε_{RA} when noise was added to the independent generalized coordinates and Model 1 was used. It is shown that noise in position variables produces a greater increment in ε_{RA} than noise in the generalized forces. This is clear, taking into to account that the LSM reduces errors in output variables (forces in this case). Similar behavior was obtained using Model 2 and 3.

The three models were used for parameter identification. The parameters identified by using Model 1 were analyzed, only 4 of the 37 parameters were below 10 times the minimum values of σ_{pi}, and some of the parameters were physically impossible. This can be noted in Table 2 (highlighted by *), where the simulated model and the identified values can be seen. The results of the number of parameters properly identified are listed in Table 3. An interesting fact is that despite Model 1 achieving the lowest ε_{RA}, the ε_{AV} was the highest values. In addition, as mentioned above, only 4 parameters were properly identified.

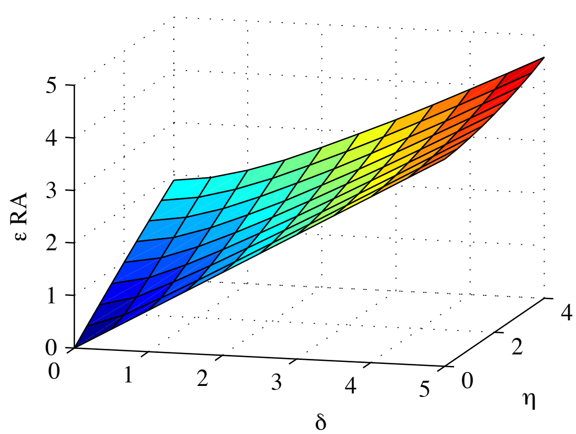

Figure 4. ε_{RA} vs δ . and η

Table 2. Some of the parameters obtained from identification using Model 1. δ=4%and η=5%.

Parameter	Exact Values	Identified Values	σ_{pi} %
$I_{zz}(4)+I_{yy}(5)$	0.1555	-86.2016*	80.1596
$I_{zz}(6)+I_{yy}(7)$	0.1555	-66.6355*	62.0087
Fv(1)	3272.0	3296.73	2.5677
$Fc^{+}(1)$	227.96	1659.0181	53.3048
$Fc^{-}(1)$	228.04	-1210.55*	73.1859
J_r+J_S	483.10	505.03	13.8778

The differences in ε_{RA} between Models 2 and 3 were about ±1.5%. Due to the fact that 12 parameters were identifiable, parameter identification was performed using only these 12 parameters (Model 4). This model includes 3 rigid body dynamic parameters related to the platform and highlighted by (†) in Table 1. The results are shown in Table (3) and are similar to those obtained by identification using Models 2 and 3. This could indicate that because of the topology of the parallel robot and in the presence of measurement noise, 12 parameters from which 3 are from the base parameter (rigid body parameter) can be used for modeling and simulating the 3-RPS parallel robot performance.

Discrepancy in Modeling

In this section the effects on the identification process when discrepancy in modeling occurs will be evaluated.

Nonlinear Model in Prismatic Joints

In this first case, nonlinear friction models are considered in prismatic joints. They can be represented by the following expression,

$$\tau_f = F_c + \left(F_s - F_c\right) e^{\left|\dot{q}/v_s\right|^{d_s}} + F_v\,\dot{q} \tag{20}$$

where, F_C, F_S and F_v are the Coulomb, static, and viscous friction coefficients respectively, v_S is the Stribeck velocity and d_s the stiction transition velocity. This model consists of five parameters and captures the Coulomb, static, viscous forces (Olsson et al., 1998). Parameters of the friction model were adjusted to simulate the behavior of the data obtained from Farhat (2006). After calculating the external original forces, noise is added and Models 1, 2, 3 and 4 are used for parameter identification.

As can be seen in Table 4, 12 parameters were identifiable. Despite ε_{RA} being similar to the one obtained without discrepancy in modeling (see Table 3), the ε_{AV} was about 50%. This indicates that for this parallel robot, despite the nonlinear tendency of the friction in prismatic joints that has been used for the simulated robot, the identification models employed do not increase the global error of the identification (ε_{RA}) considerably. Although large errors for the identified parameters were found, this is due to the fact that discrepancies in modeling are "shared" among the parameters which can be properly identified (12 parameters).

Table 3. Results of ε_{RA} and ε_{AV} from different model and δ=4%and η=5%.

Model	ε_{RA} %	ε_{AV} %	Number of Parameters
1	4.57	5.37	37/4
2	4.58	2.94	24/12
3	4.63	3.06	18/12
4	4.73	3.17	12/12

Table 4. Results of ε_{RA} and ε_{AV} from different model and δ=4%and η=5%.

Model	ε_{RA} %	ε_{AV} %	Number of Parameters
1	4.50	52.18	37/4
2	4.60	54.88	24/12
3	4.69	57.02	18/12
4	5.16	59.02	12/12

Neglecting Friction in Rotational Joints

In this case, linear friction models were considered in the revolution joints. The parameters of the friction models are chosen to be about 15 % of the friction in prismatic joints. This assumption is reasonable considering that ball bearing friction is relatively small compared with the friction in linear actuators of the actual robot. The parameter identification models neglect friction at rotational joints. Identification was addressed considering noise in measurement. After identification was carried out, as can be seen in Table 5, for Models 3 and 4, only 12 parameters could be properly identified. Table (5) also presents the ε_{RA} and ε_{AV} for δ=4%and η=5%.The results are very similar. For experimental parameter identification of the actual robot, it can be said that a reasonable assumption is to neglect friction in rotational joints.

Table 5. Results of ε_{RA} and ε_{AV} from neglecting friction at Rotational Joins δ =4%and η =5%.

Model	ε_{RA} %	ε_{AV} %	Number of Parameters
1	5.30	3.13	37/3
2	5.28	3.72	24/10
3	5.33	3.76	18/12
4	5.36	3.80	12/12

Table 6. Results of ε_{RA} and from neglecting Actuator Dynamics

Model	ε_{RA} %	Number of Parameters
1	2.05	37/15
2	7.25	24/13
3	7.63	18/11
4	18.70	12/8

Neglecting Actuator Dynamics

The assumption of neglecting actuator dynamics is evaluated in this last case. In Table 6 the ε_{RA} are listed, along with the number of parameters properly identified obtained considering Models 1-4. In these cases the error using the 4 models are quite different. Model 1 presents a ε_{RA} that can be considered good for model validation, but if the parameters from the identification are observed in detail they include some values with a non-physical meaning. This fact is shown in Figure 5, where forces due to friction and rigid body are displayed separately.

As can be observed in Figure 5, both the Inertial and Friction parts have unreasonable values. Nevertheless, as a whole, measurement forces and identified forces are similar. The discrepancy in ε_{RA} of the different models used highlights that neglecting actuator dynamics for parameter identification for the actual robot analysis is a rash assumption. Besides, another interesting aspect can be appreciated from Table 6. The variance analysis of Model 1 gives more parameters than model 4 but with some parameter with values unfeasible. Therefore, this analysis cannot be used alone as a criteria for finding the parameter which can be properly identified. A general methodology for finding this parameter has to include both variance analysis and physical feasibility.

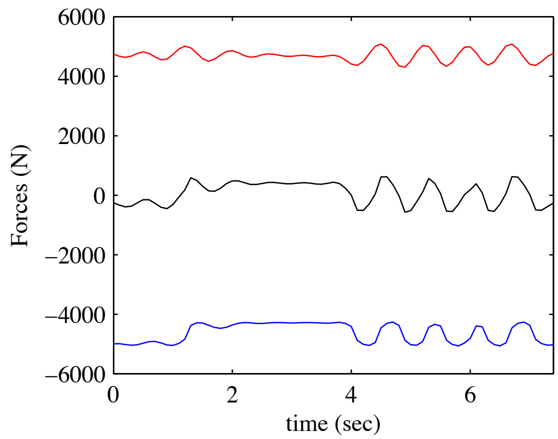

Figure 5. The results from parameter identification Neglecting Actuator dynamics and using Model 1. Inertial Forces -red, Friction Forces –blue, Total Forces –black.

APPLICATION TO THE ACTUAL 3-RPS ROBOT

The results from previous section can be summarized as follows,

- Rotor and screw inertia have to be considered.
- Friction in passive joints, like rotational joints, can be neglected. This assumption is based on the fact that there is not a considerable increment of error on the identified parameters.
- In the presences of noise only 12 parameters are expected to be properly identified.

Taking these results into account, a parameter identification process was applied over an actual parallel 3-RPS robot. A PID controller was used in order to determine the control actions that were applied with a frequency of 100Hz, at which measurement was also performed. The total duration of the optimized trajectory was 7.5s. Trajectories were repeated several times, the applied control actions were averaged and then, filtered by a second order lowpass digital Butterworth. For the identification process, 750 configuration points are extracted every 0.01s. The position of the motor was measured by means of incremental encoders. Velocity and acceleration were derived in analytical from deriving the Fourier finite series (Swevers et al., 1997b) obtained from fitting the position data to the Fourier series. A linear relation between the control actions and torques was assumed.

Comparing Table 7 and Table 3, the level of ε_{RA} in the actual manipulator was doubled, but the number of parameters properly identified was found to be similar (12 for Model 4). The identified base parameters of the links of Models 1 and 4 are presented in Table 8 along with those of the simulated manipulator. As can be observed, the identified parameters of the actual manipulator using Model 4 and the original CAD values of the simulated manipulator are comparables contrary to those identified using Model 1 where a significant difference appears. On the other hand, parameters from Model 1 have significant differences with respect to the simulated ones.

The fact that 12 parameters can be properly identified is reasonable. On the one hand, the topology itself of the parallel robot does not allow the finding of well-excited trajectories. Additionally, some base parameters make little contribution to the dynamic behavior of the model; for example, during movement the accelerations of the limbs were smaller than the platform. On the other hand, the friction of the linear actuator of the real robot was found to be high, thus complicating even more the identifiability of the rigid body parameters.

Table 7. ε_{RA} from Actual 3-RPS Robot

Model	ε_{RA} %	Number of Parameter
1	8.40	37/2
2	8.43	24/9
3	8.53	18/12
4	8.62	12/12

Finally, Model 4 was validated. The parameters obtained for one trajectory were used to compute the forces for a new one that had not been previously used for identification. Figure 6 depicts the comparison, the estimated forces and measurements are very close.

Table 8. Rigid Body Base Parameter Model 1 vs Model 4.

Base Parameter	CAD	Real Robot Model 4	Real Robot Model 1
mx(3)+0.5774my(3) - 0.4563(m(3)+m(2))	-2.47	-2.59	1.16
m(5)-2.531my(3)+m(3)+m(2)	10.83	13.72	-3.29
m(7)+2.531my(3)	5.42	6.95	-0.557

CONCLUSIONS

In this paper, the dynamic modeling and parameter identification of an actual ball screw driven 3-RPS parallel robot was carried out. To achieve that, a simulated robot was built in such a way that its dynamic behavior was as close as possible to the actual one. This simulated robot allowed the evaluation of discrepancies in modeling and noise measurement in the identification process. For this evaluation four dynamic models were developed. The study of which parameter subjacent in the model could be properly identified was also considered and was based on analyzing the relative standard deviation of each parameter and considering physical feasibility. It was found that due to the effect of noise, the base parameters are not completely identifiable. Indeed, because of the topology of the parallel robot and due to the high friction of the linear actuator of the real robot, 12 parameters could be properly identified. For this paper a simulated robot was necessary for studying and evaluating models used on the identification. For future work it is hoped to find a systematical approach based on statistical frameworks and physical feasibility for studying the identifiability of the dynamic parameter, without the necessity of a simulated robot.

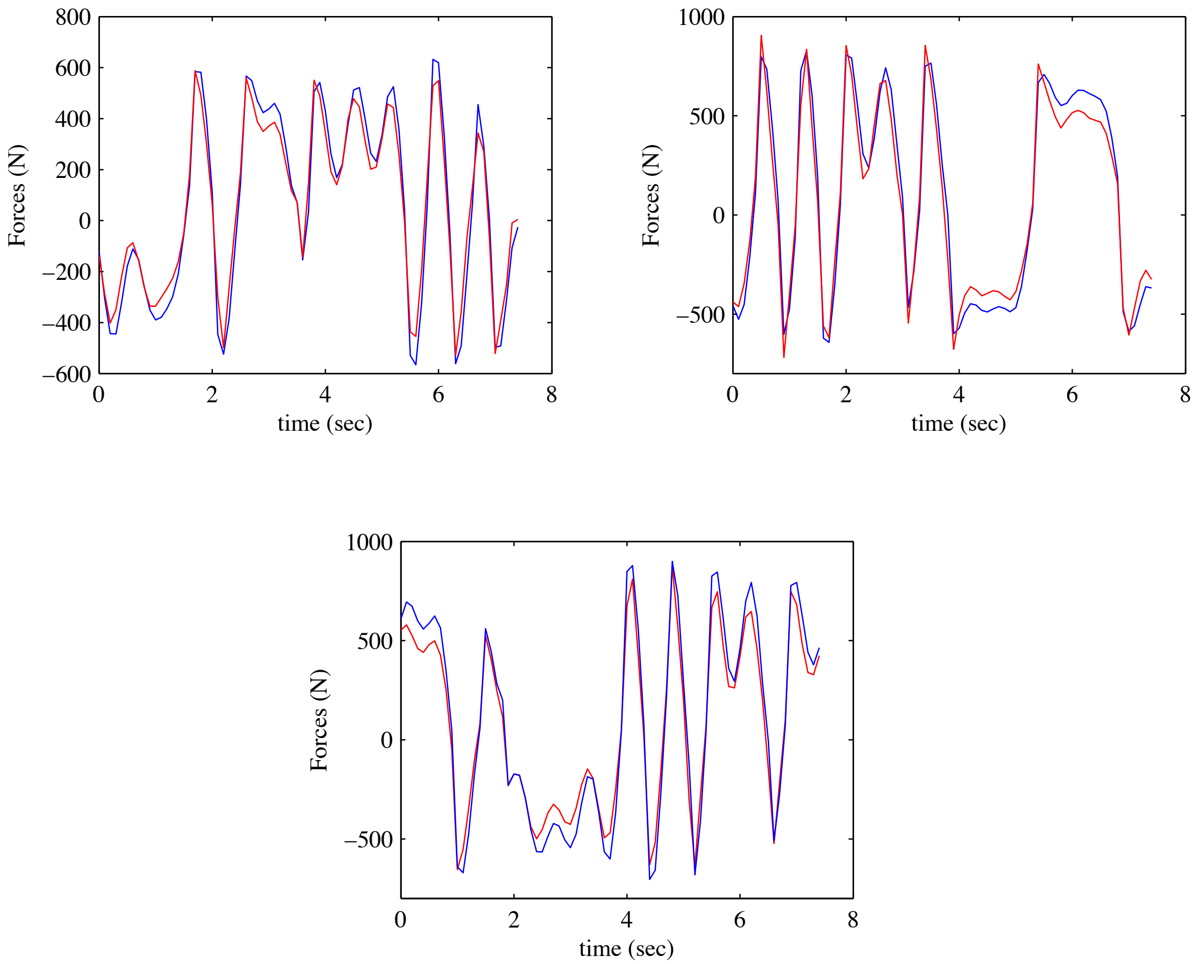

Figure 6. Measurement Forces (-red) and Forces from Identified Parameter (–o blue)

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