IDENTIFICATION OF THE DYNAMIC PARAMETERS OF THE C5 PARALLEL ROBOT

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Abstract: This paper deals with the experimental identification of the dynamic parameters of the C5 parallel robot. The inverse dynamic model of the robot is formulated under the form of linear equation with respect to the dynamic parameters. Moreover, a heuristic procedure for finding the exciting trajectory has been conducted. This trajectory is based on Fourier series whose coefficients are determined by using a heuristic method. The least squares method has been applied to solve an over-determined linear system which is obtained by sampling the dynamic model along the exciting trajectory. The experimental results show the effectiveness of the identification procedure.

1 INTRODUCTION

A parallel architecture is a closed-loop mechanism in which the end-effector (mobile platform) is connected to the base by at least two independent kinematic chains. The pioneering works in this field are those of Stewart who proposed in 1965 a parallel platform with 6 DOF. Since then, several authors have proposed a large variety of designs and studies. Parallel architectures were first used for building flight simulators and tire testers. Since then, they were used in other applications like the handling of heavy objects with great accelerations, or the assembly of parts requiring high precision. More recently, parallel robots appeared in the medical field . The latter requires the design of very precise parallel machines performing in a limited workspace

Because of their structure, serial robots have limited dynamic performances. In the other hand, due to their reducted inertia, parallel robots allow for the reduction of coupling dynamic effects and consequently to better dynamic performance.

In the literature, several techniques were proposed for the identification of dynamic parameters of robot. A CAD method based on identifying inertia parameters is proposed in (An et al, 85). Usually these methods lead to an unsufficient precision of inertia parameters estimation and do not allow for the determination of other dynamic parameters (viscous friction, coulomb friction). For better results, an estimation of the whole dynamic parameters of the assembled robot is required.

The identification procedure consists usually of four main steps: (1) Calculation of an identifiable dynamic model, (2) Generation of the optimized excitation trajectory, (3) Estimation of the dynamic parameters, and finally (4) Validation of the obtained model.

The first step consists of calculating the minimal set of dynamic parameters to be identified (set of base parameters). This set can be computed by using the QR decomposition of observation matrix (Gautier, 91). In the second step, the optimal exciting trajectory is calculated in order to guarantee the relevance of the measured data. This step includes the choice of an optimization criterion.

The third step consists of estimating the dynamic parameters from the measured data. Least squares method is one of the most widely used estimation method. It consists of solving an over-determined linear system (Janot, 07). An improvement over the classical LS method is the use of a Weighted Least Squares (WLS) estimator, (Renaud et al, 06). Another approach is the Maximum Likelihood Estimator(MLE) whose principle assumes that the true parametric model is known exactly (Swevers et al, 97). Other estimators like the ellipsoidal algorithm or the interval analysis (Poignet et al, 03) have been proposed in the literature.

The fourth step of identification procedure consists of validating the identified dynamic model. In most cases, this is realized by comparing the predicted and the measured torques for a trajectory which is different from the exciting trajectory.

In this paper we present the identification of dynamic parameters of the 6 DOF parallel robot with C5 joints. First, the dynamic model is expressed as a linear relation with respect to the dynamic parameters. The parameters are estimated by the classical technique of least squares solving an overdetermined linear system obtained from a sampling of the dynamic model, along the exciting trajectory.

The paper is organized in four sections. First one describes the mechanical architecture of the C5 parallel robot. Second section presents the inverse dynamic model of the robot. Section 3 presents an estimation of the dynamic parameters of the robot. Calculation of the exciting trajectory along with the data filtering procedure are developed in section 4. Fifth section is dedicated to the presentation and analysis of the experimental results including the cross validation procedure. Finally, a conclusion and some perspectives are given in the last section.

2 DESCRIPTION OF THE C5 PARALLEL ROBOT

The C5 parallel robot consists of a static part and a mobile part connected together by six actuated links. Each segment is embedded to the static part at point A_i and linked to the mobile part through a spherical joint attached to two crossed sliding plates at point B_i (Fig. 1).

Theoretical study concerning this architecture has been presented in the literature. The C5 links parallel robot is equipped with six linear actuators; each of them is driven by a DC motor. Each motor drives a ball and screw arrangement. The position measurements are obtained from six incremental encoders, which are tied to the DC motors.

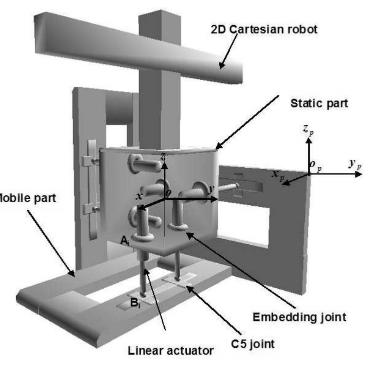

Figure 1: Parallel robot.

3 MODELING OF THE C5 ROBOT

3.1 Inverse Dynamic Model

The inverse dynamic model of the C5 parallel robot is given in (Khalil et al, 04):

To solve our identification problem, we rewrite the inverse dynamic model to make it linear with respect to dynamic parameters (Poignet et al, 02). The dynamic model is rewritten then as follows:

$$\Gamma = D(\omega_p, \dot{\omega}_p, \dot{V}_p, q, \dot{q}, \ddot{q})\; X_s \tag{1}$$

with

- Γ : (6×1) torque vector
- D : (6×34) observation matrix
- X_s : (34×1) standard parameters vector:

$$\begin{aligned}
X_s &= (X_{s1} \quad X_{s2} \quad X_{s3} \quad X_{s4} \quad X_{s5})^T\\
X_{s1} &= (M_1\ \ M_2\ \ M_3\ \ M_4\ \ M_5\ \ M_6\ \ M_p)\\
X_{s2} &= (XX\ \ XY\ \ XZ\ \ YY\ \ YZ\ \ ZZ\ \ MX\ \ MY\ \ MZ)\\
X_{s3} &= (I_{a1}\ \ I_{a2}\ \ I_{a3}\ \ I_{a4}\ \ I_{a5}\ \ I_{a6})\\
X_{s4} &= (F_{v1}\ \ F_{v2}\ \ F_{v3}\ \ F_{v4}\ \ F_{v5}\ \ F_{v6})\\
X_{s5} &= (F_{s1}\ \ F_{s2}\ \ F_{s3}\ \ F_{s4}\ \ F_{s5}\ \ F_{s6})
\end{aligned}$$

4 DYNAMIC PARAMETERS IDENTIFICATION

For the purpose of dynamic parameters identification, we use the formulation given in (Janot et al, 07). The principle of identification consists in sampling the inverse dynamic model of the robot with respect to the base parameters, obtained by QR decomposition (Gautier, 91) along the exciting trajectory. A filtering process is applied to the measured data in order to obtain a good estimation of dynamic parameters. This technique allows us to obtain an over-determined linear system of full rank.

5 EXCITING TRAJECTORY CALCULATION

The quality of the exciting trajectory can be evaluated through a good condition number of the regressor matrix. The calculation of this trajectory can be done by nonlinear optimization. In our case, we used an exciting trajectory based on Fourier series (Swevers et al, 91). For each segment j $(j = 1, 2, \ldots 6)$, the position q_j can be written as follows:

$$q_j(t) = q_{j,0} + \sum_{k=1}^{M} (a_{j,k} \sin(k\omega_f t) + (b_{j,k} \cos(k\omega_f t)) \quad (2)$$

with

- ω_f the fundamental pulsation of the finite Fourier series.
- t the time.
- $a_{j,k}$ and $b_{j,k}$ $(k = 1, ...5)$ the amplitudes of sine and cosine functions
- $q_{j,0}$ is the initial value of the position trajectory.

In order to excite the robot in the bandwidth of the position closed loop, $f_{dyn} < 2\,Hz$, we have chosen the fundamental frequency of trajectories equal to $0.1Hz$ and the number of harmonics $k = 5$.

As the number of Fourier series coefficients is high, it is difficult to determine them by a nonlinear optimization. For this reason, we calculate these coefficients in a heuristic way. The calculation of these parameters is based on the motion constraints which are imposed by physical limitations of robot. These constraints can be expressed as follows:

$$-0.05m < q_j(\alpha) < +0.05m \quad (3)$$

$$-0.1m/s < \dot{q}_j(\alpha) < +0.1m/s \quad (4)$$

$$-0.5m/s^2 < \ddot{q}_j(\alpha) < +0.5m/s^2 \quad (5)$$

Where:

Vector α includes the trajectory parameters $q_{j,0}$, $a_{j,k}$ and $b_{j,k}$.

The heuristic approach allows us to find the exciting trajectories shown in Fig. 2.

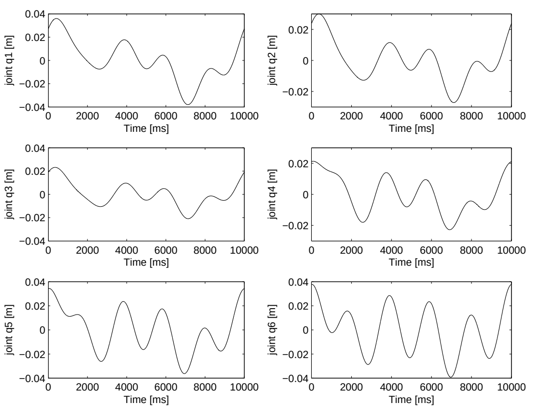

Figure 2: Exciting trajectories.

5.1 Data Filtering

For a good estimation of the dynamic parameters, the measurements signals need to be filtered . So the position is filtered by the 4^{th} order Butterworth filter. The vector Y and each column of matrix W are filtered by the 8^{th} order Tchebychev filter and are resampled at lower rate in order to reject the high frequency ripples of the measured torques. The computation of joint velocities and accelerations is made by using the central difference algorithm in order to avoid any distortion of phase and amplitude.

6 EXPERIMENTAL RESULTS

The table given in Fig. 3 shows the estimated base parameters. The relative standard deviations are also given.

parameters	identified values $\hat{X}$	relative standard deviations $\%\sigma_{\hat{X}jr}$
$M_1 + I_{a1}(kg)$	0.5435	7.0629
$M_2 + I_{a2}(kg)$	0.4075	11.3082
$M_3 + I_{a3}(kg)$	0.5436	7.0617
$M_4 + I_{a4}(kg)$	0.5909	6.7516
$M_5 + I_{a5}(kg)$	0.4909	8.8692
$M_6 + I_{a6}(kg)$	0.5718	6.7108
$M_p(kg)$	8.2652	9.6980
$XX(kg.m^2)$	0.1035	1.7892
$YY(kg.m^2)$	0.2124	5.8701
$ZZ(kg.m^2)$	0.0178	7.0021
$MX(kg.m)$	7.5925	2.0799
$MY(kg.m)$	-1.8212	8.6681
$MZ(kg.m)$	21.2650	16.1002
$F_{v1}(N.m.s.rad^{-1})$	8.8464	2.0209
$F_{v2}(N.m.s.rad^{-1})$	7.9940	2.2183
$F_{v3}(N.m.s.rad^{-1})$	8.7253	2.1198
$F_{v4}(N.m.s.rad^{-1})$	7.5517	2.2366
$F_{v5}(N.m.s.rad^{-1})$	8.1706	2.2777
$F_{v6}(N.m.s.rad^{-1})$	8.7312	2.1182
$F_{s1}(N.m)$	0.5034	5.1484
$F_{s2}(N.m)$	0.3424	7.4246
$F_{s3}(N.m)$	0.2344	9.3723
$F_{s4}(N.m)$	0.2705	8.3329
$F_{s5}(N.m)$	0.1753	13.1492
$F_{s6}(N.m)$	0.2335	9.4081

Figure 3: Identified parameters.

Note that the dynamic parameters present in most cases a relative standard deviation lower than 10%, which represents a good estimation. However the relative standard deviation of the parameters MZ, and F_{S5} is higher than 10%. This deviation is due to mechanical constraints, consequently, we conclude that the obtained results are encouraging and we can state that these identification results are globally acceptable.

In order to validate the estimated dynamic parameters, we proceed to a cross validation which consists in comparing the measured torques with those obtained by the inverse dynamic model with the identified parameters. The trajectory which is used for this validation has not been used previously for the identification. Figure 4 show the results of this validation. For the others axis, we have also obtained the same ting than figure 4

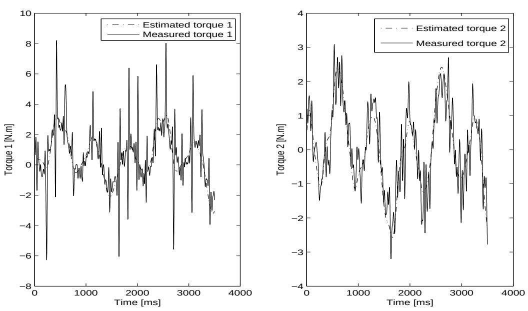

Figure 4: Estimated and measured torque for the joints 1 and 2.

Note that the calculated torques using the inverse dynamic model with the estimated parameters are close to those measured on the robot. Consequently, one can conclude that the estimation of the dynamic parameters, using the least squares method is valid.

7 CONCLUSIONS

In this paper, we identified the physical parameters of the C5 parallel robot. The identification is based on the least squares method. The application of this identification method uses an exciting trajectory calculated from a heuristic approach. To validate the identified parameters, we considered another trajectory different from that used in identification. The cross validation enables us to conclude with the effectiveness of the considered identification. In short term of our project, we propose to include the joint elasticity, which is the major source of flexibility in many practical applications.

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