Control of Parallel Manipulators for Very High Accelerations: The Mechanical Vibrations Issue

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CONTROL OF PARALLEL MANIPULATORS FOR VERY HIGH ACCELERATIONS: THE MECHANICAL VIBRATIONS ISSUE

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Abstract. *This paper deals with the issue of mechanical vibrations in control of parallel robots. The proposed control strategy consists in a nonlinear adaptive dual mode controller applied to the actuation redundant parallel manipulator Par2. In this context, the experimental testbed is not equipped with velocity sensors. Therefore, a high-gain observer has been used to estimate the articular velocities. Real-time experiments show the effectiveness of the proposed control scheme, as well as the arised mechanical vibrations that increase with acceleration (becoming an important issue for accelerations higher than 20G). Some promising possible solutions to deal with the problem of mechanical vibrations have been discussed for future implementation.*

Keywords: *Nonlinear Adaptive Control, Trajectory Tracking, Parallel Robots, Pick-and-Place, Mechanical Vibrations*

1. INTRODUCTION

The mechanical vibrations consist in an important issue for many different areas, such as robotics (spatial manipulators (Jiang, 2008), industrial manipulators ((Algermissen, 2005), (Incerti, 2008) and (Franke, 2009)), aeronautics (Wilkie, 1996), nanopositioning (Aphale, 2009), automobile vehicles (Scheidt, 1999), etc.

The vibration of the platform is a problem that frequently takes place during the operation of an industrial robot, in particular during the execution of high-speed movements (Incerti, 2008). With the increasing requirements in machine speed and accuracy, reduction of structural vibrations becomes more and more important (Algermissen, 2004), as vibrations make the process' results worse and shorten the lifecycle (Ohira, 1993).

During the last decades, vibration compensation/damping has been widely studied. In (Algermissen, 2005), a Robust-Gain-Scheduling for robust H_∞ controller was used on piezoceramic stacks serving as both sensors and actuators that provide the means to suppress the vibrations. A numerical study concerning the active vibration control of smart piezoelectric beams has been presented in (Vasques, 2006), with a comparison between classical control strategies (constant gain and amplitude velocity feedback) and optimal control strategies (Linear Quadratic Regulator and Linear Quadratic Gaussian). In (Jiang, 2008), a vision-based control approach was proposed to deal with the vibration appearing at the end-point of a flexible-link manipulator. A motion planning procedure aimed to vibration control of industrial robots for assembly operations was described in (Incerti, 2008). In (Yang, 2009), a robust backstepping control approach was derived to solve the active vibration isolation problem using a Stewart platform (Yang, 2008). A novel approach for vibration damping of a multi-link flexible arm with Fiber-Bragg-Grating sensors was presented in (Franke, 2009). In (Aphale, 2009), a hybrid control scheme comprising a loop-shaping H_∞ controller and an inversion-based feedforward control scheme was proposed for a 2-dof piezoelectric-stack actuated platform. The objective of this control scheme was to deliver accurate nanopositioning performance at relative high speeds (up to 40Hz), which cause intense vibrations in open loop.

In this paper, the problem of control of the Par2 parallel robot (Pierrot, 2009) is addressed. The proposed solution is based on a nonlinear dual mode adaptive controller (Hsu, 1994). It is shown in this study that, by increasing the robot's acceleration to 20G, some vibrations can be noticed. Considering that our objective is to reach higher accelerations (up to 40G), this issue will become very important.

This article is organized as follows: In section 2, a description of the Par2 testbed is presented. In section 3, the proposed control scheme is detailed. Section 4 is devoted to the experimental results and their interpretation. In section 5, the current results and the proposed solutions for the compensation/damping of the vibrations are discussed.

2. PAR2 PROTOTYPE: DESCRIPTION AND DYNAMICS

2.1 Description of the Par2 testbed

The proposed experimental platform is a two-dof parallel manipulator, named Par2 (represented in Fig. 1), with the following characteristics:

- the platform ⑥ is a rigid body,
- only the two inner arms ③ are actuated,
- the two other arms ④ are linked to the frame ① through passive revolute joints,
- inner arms ③ and ④ are connected to ⑥ with pairs of rods ⑤ mounted on ball joints ⑦,
- the rotations of the arms ④ are coupled in order to guarantee planar motions along x and z axes.

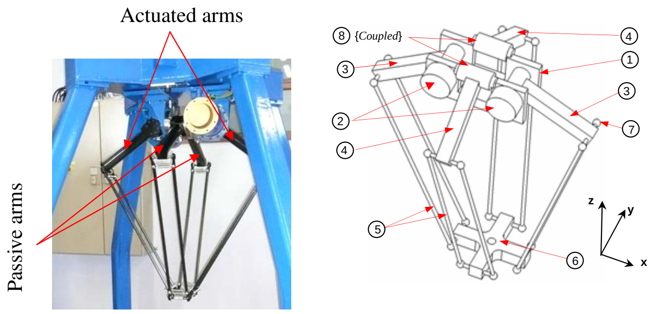


Figure 1. The 2-dof parallel manipulator Par2: view of the robot (left), Schematic view of its mechanical structure (right)

The proper functioning of this two-dof parallel manipulator is guaranteed by the coupling of the rotation of arms ④. This constrains the robot's platform to evolve in one plane. The *coupling* means that the rotation of the first arm in the clockwise direction involves the rotation of second one in the counterclockwise direction.

2.2 Nonlinear dynamic model of the Par2 robot

The application of Lagrange formulation ((Spong and Vidyasagar, 1989) and (Sciavicco and Siciliano, 1996)) to the above described mechanical structure leads to the following dynamic model:

$$I_{eq}\begin{bmatrix}\ddot{q}_1\\ \ddot{q}_2\end{bmatrix} = \tau - f_d\begin{bmatrix}sign(\dot{q}_1)\\ sign(\dot{q}_2)\end{bmatrix} - f_v\begin{bmatrix}\dot{q}_1\\ \dot{q}_2\end{bmatrix} - \frac{g}{2}(M_1+M_2)\begin{bmatrix}L_1\cos(q_1)\\ L_2\cos(q_2)\end{bmatrix} + J^T\left(M_p\dot{J}(q,\dot{q})\dot{q} - g\begin{bmatrix}M_p\\ M_p\end{bmatrix}\right) \tag{1}$$

where $I_{eq} = I_{drv} + I_f + I_a + J^T M_p J$, I_{drv} is the motor driver inertia, I_f is the forearm inertia, I_a is the arm inertia, J is the jacobian matrix, M_p is the mass of the platform of the robot, g is the gravitational acceleration, f_v is the viscous friction coefficient, f_d is the dry friction coefficient, M_1 and M_2 are the masses of the arms, L_1 and L_2 are their lengths. This dynamic model can be written in the following matrix form:

$$D(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + f(q,\dot{q}) = \tau \tag{2}$$

where $D(q)$ and $C(q,\dot{q}) \in \mathbb{R}^{2\times 2}$ are the inertia and the centrifugal and Coriolis matrices, respectively; $G(q)$ and $f(q,\dot{q}) \in \mathbb{R}^2$ are the gravitational forces and the friction forces vectors; $\tau \in \mathbb{R}^2$ is the vector of control inputs (torques generated by the actuators); $q = \begin{bmatrix}q_1\\ q_2\end{bmatrix}$, $\dot{q} = \begin{bmatrix}\dot{q}_1\\ \dot{q}_2\end{bmatrix}$ and $\ddot{q} = \begin{bmatrix}\ddot{q}_1\\ \ddot{q}_2\end{bmatrix} \in \mathbb{R}^2$ are the vectors of articular positions, velocities and accelerations, respectively.

3. PROPOSED SCHEME: A NONLINEAR DUAL MODE CONTROLER

The Dual Mode controller, originally referred as *'binary'* in (Hsu and Costa, 1994) consists basically in the utilization of a high adaptation gain together with a projection of the estimated parameters. Then, to large tracking errors in the transitory stage, the controller behaves approximately as a sliding mode controller, generating an exponential convergence to a residual domain arbitrarily small, and to smaller errors, he behaves as a parametric adaptation law. Other important advantages of the adaptation law in dual mode with respect to other adaptation laws or known robust control algorithms are the generation of continuous control signals, the improvement of the robustness of the system and the limitation of the values of the estimated parameters through a projection, which has the effect of reducing the effective gain of the controller when the tracking error increases (reducing the sensibility to measuring noises).

The control method proposed in this work is a nonlinear Dual Mode controller (Hsu, 1994) derived from the nonlinear adaptive controller proposed in (Slotine, 1988), with the addition of the projection on the law of the parametric adaptation, and can be written as:

$$\tau = Y\hat{a} + K.s + \bar{d}Sat(\alpha s) \tag{3}$$

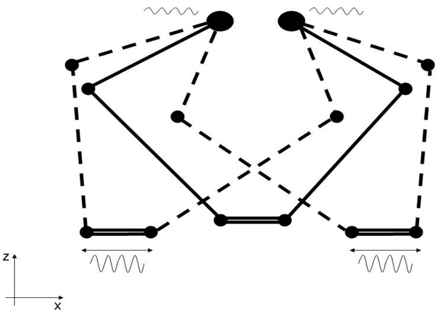
where $s = \dot{\tilde{q}} + \lambda\tilde{q}$, being $\tilde{q} = q_d - q$, $\dot{\tilde{q}} = \dot{q}_d - \dot{q}$; λ, $\bar{d}$, α and K are positive constants, $Sat(\alpha s) = \frac{\alpha s}{||\alpha s||+1}$ is a continuous function with respect to its argument (with continuous partial derivatives and components limited to the interval $[-1, +1]$). The vector $\hat{a}$ represents an estimate of the unknown parameters of the system given by the vector a, and Y is the regressor vector (based on the dynamic model of the system). The reader is referred to (Sartori-Natal, 2009) for the details about the estimation of the articular velocities (as only the positions are measured) with a High-Gain Observer (HGO) (Khalil, 1997), the adaptation of the estimated parameters ($\hat{a}$) and the calculation of the regressor vector (Y).

4. REAL-TIME EXPERIMENTAL RESULTS

The objective of this section is to present the real-time experimental results obtained with the application of the proposed control scheme described in section 3 to the Par2 parallel manipulator described in section 2. The platform moves in the XOZ plane (being X the horizontal axis and Z the vertical axis). The desired cartesian trajectory to be tracked by the Par2 parallel robot is a usual *'pick-and-place'* trajectory, and its parameters are described in table 1. In this experimental scenario, for one cycle, the robot has to go from the initial cartesian position (x_{d_i}, z_{d_i}) to the desired final cartesian position (x_{d_f}, z_{d_f}) and then return to the initial one (x_{d_i}, z_{d_i}). The corresponding cartesian reference trajectories and the illustration of the robots movements and possible vibrations in xoz plane are plotted in Fig. 2.

Table 1. Parameters of the cartesian reference trajectory

Parameter	Description	Value
(x_{d_i}, z_{d_i})	Initial desired cartesian position in the plane XOZ	(-0.35 m,-0.95 m)
(x_{d_f}, z_{d_f})	Final desired cartesian position in the plane XOZ	(0.35 m,-0.95 m)
$\dot{x}_d^{max}$	Maximum cartesian velocity	$6\ \&\ 8 m/s$
$\ddot{x}_d^{max}$	Maximum cartesian acceleration	$15\ \&\ 20 G$



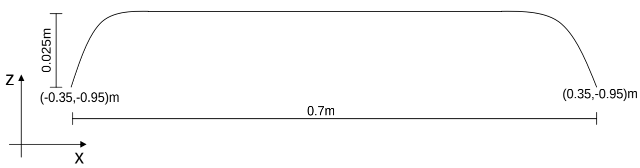


Figure 2. Illustration of the robot's movements (left) and the desired cartesian trajectory x-z in a larger scale (right)

Based on these trajectories and using the inverse geometric model of the robot (Pierrot, 2009), the articular reference trajectories are computed. The trajectory tracking generated by the DM controller for 20G and its control signal are shown in Fig. 3. A zoom on the stop point of the articular positions is shown in Fig. 4 and a zoom on the stop point of the control inputs is shown in Fig. 5. The real-time implementation of the DM controller for the proposed scenario, namely usual *pick-and-place*, was made with a sampling time of $0.5\,msec$.

In (Sartori-Natal, 2009), a comparison between the Dual Mode controller and a conventional Proportional-Derivative (PD) controller was presented and discussed. In this paper, the objective is to emphasize the mechanical vibrations issue.

By analyzing Fig. 4, it is possible to notice the increase of the vibrations on the articular positions (in amplitude and in duration) caused by the increase of the acceleration from 15G to 20G, which caused an amplification on the vibrations of the control signals (Fig. 5). As shown in Fig. 2, the mechanical structure of the robot (which is not absolutely rigid) will cause an amplification of the vibrations on the platform. This means that even relatively small articular vibrations may cause relatively big vibrations on the platform. In order to avoid an undesired behaviour of the system (loss of precision, or even damages to the mechanical structure of the robot) for higher accelerations, the following solutions shall be investigated:

Solution 1. The optimization of the reference trajectories: This solution deals with the optimization of the reference trajectories with respect to some variables, such as maximum torques, maximum accelerations/decelerations, etc. In our case, the objective of the parametrization and the optimization of these parameters would be to minimize the arised mechanical vibration on the stop points, as illustrated in Fig. 6.

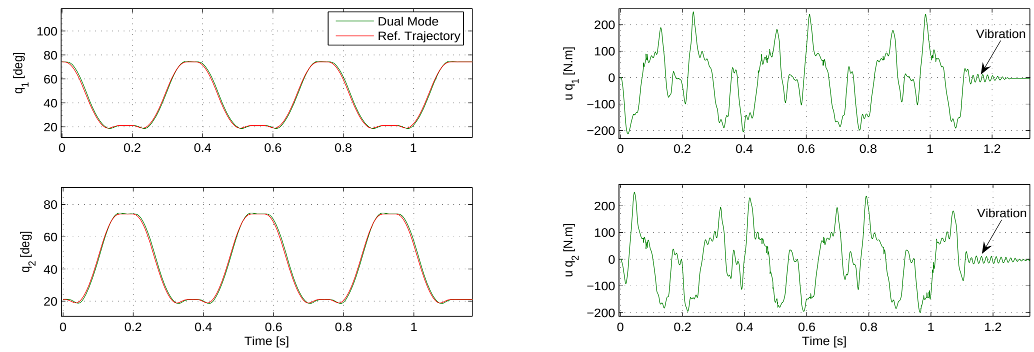


Figure 3. Articular trajectory tracking (left) and the torques (right) obtained by the DM controller for 20G

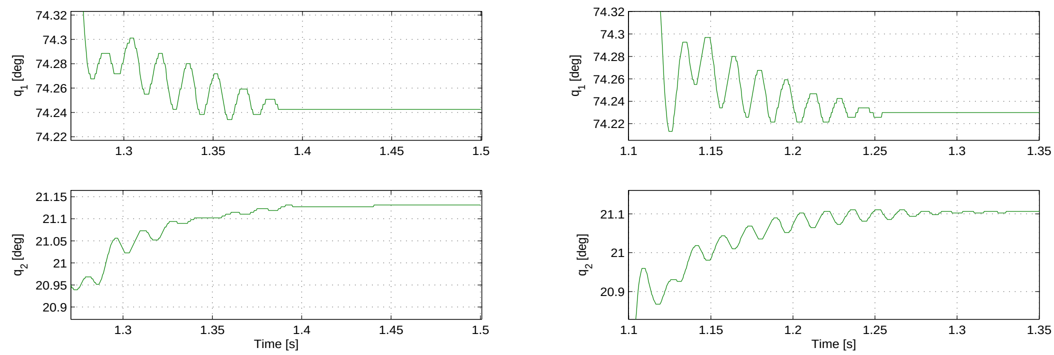


Figure 4. Zoom on the stop point of the Dual Mode's trajectory for 15G (left) and for 20G (right)

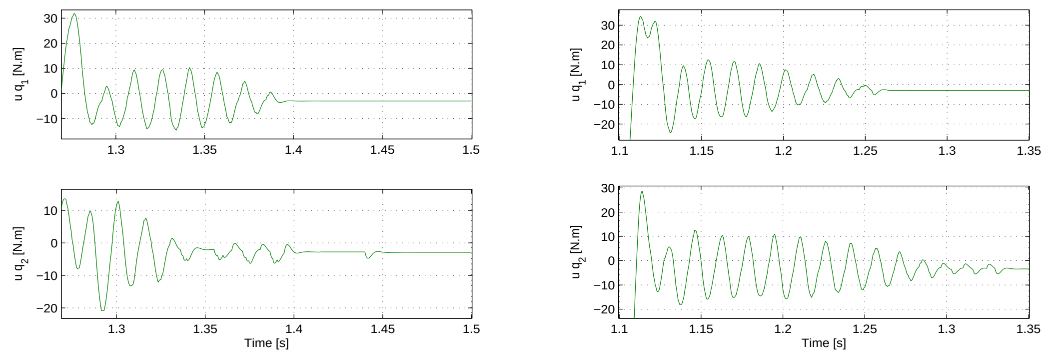


Figure 5. Zoom on stop point of the torques for 15G (left) and for 20G (right)

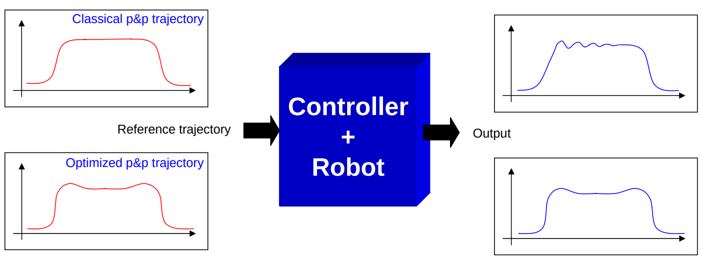


Figure 6. Effect of the *pick-and-place* (p&p) reference trajectories' optimization on mechanical vibrations' reduction

Solution 2. The utilization of piezoelectric actuators on the robot's arms: Controlled piezoelectric actuators can be used to damp/compensate vibrations. For that, the basic idea consists in generating adequate forces against arised vibrations. The first step of this solution is to attach piezoelectric actuators on the robot's arms. Fig. 7 shows the piezoelectric patches and how they are fixed (glued) on the arms. The Par2's arms equipped with the piezoelectric patches are shown in Fig. 8. The basic principle of sensing/actuation scheme used in (Vasques, 2006) is presented in Fig. 9, with $F(t)$ being the initial displacement field and $w(t)$ the white noise force disturbance. In the aim to test the piezoelectric actuators in our case, the experimental setup of Fig. 10 was carried out.

Figure 7. Piezo patch (top) and its fixation process (bottom)

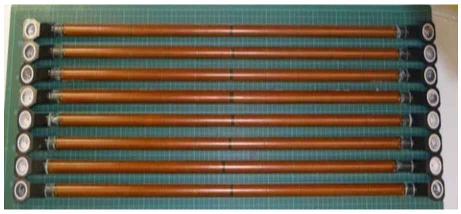


Figure 8. Par2's arms equipped with the piezo patches

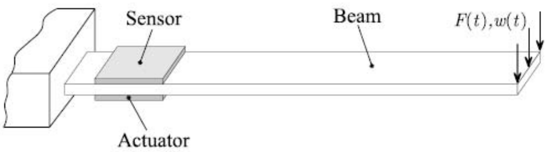


Figure 9. Diagram with the sensing/actuation scheme of the proposed solution in (Vasques, 2006)

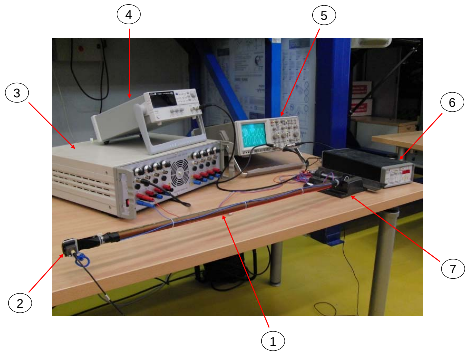


Figure 10. Experimental setup of the piezo-actuators

The scheme used in (Vasques, 2006) consisted in using piezo patches as sensors and also as actuators. In our tests, an accelerometer on the platform is used as a sensor instead. In Fig. 10, 1 is the beam (robot's arm), 2 is the accelerometer, 3 is the amplifier (which has as an input signal between -10V and 10V, and an output signal between 0 and 400V), 4 is the low frequency signal generator, 5 is the oscilloscope, 6 is the signal conditioner for the accelerometer and 7 is the base where the beam is fixed. In the moment, an identification process is under development, such that an adequate model is obtained and, based on this model, a performant controller can be designed in the future.

Solution 3. The consideration of the arms' flexibility in the design of the controller: During the design of the Dual Mode controller, the Par2 robot was considered rigid, which is not absolutely correct. The objective, when adopting this solution, is to take into account the vibrations in the dynamic model of the robot and to compensate them in the controller. For instance, in (Ryu, 2004) a new method to control a flexible manipulator with noncollocated output was implemented in simulation, and a good control performance was obtained. The noncollocated output means that, instead of the joint velocity (v_a), the end-point velocity (v_e) is fedback to the controller through the link dynamics (shown in Fig. 11).

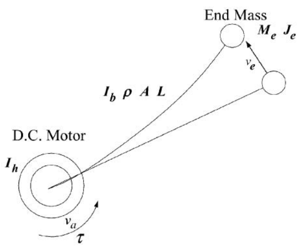


Figure 11. Diagram of the flexible arm used in (Ryu, 2004)

5. CONCLUSIONS AND FUTURE WORKS

This paper deals with the mechanical vibrations issue in the control of parallel manipulators for very high accelerations. Indeed, if our main objective is to achieve a precise trajectory tracking for very high accelerations, one of the main difficulties for this task is the increase of the mechanical vibrations with the increase of the accelerations. With a maximum acceleration of 15G and a maximum velocity of 6m/s, almost no vibrations were noticed, while with 20G and 8 m/s, small vibrations were noticed at the stop points of the performed movements. In the future, experiments will be done for higher accelerations, so it will be needed to cancel/damp these vibrations, as they can cause an important loss of precision or even cause damages to the mechanical structure of the robot. Some possible solutions have been discussed to deal with this issue, such as the optimization of the pick-and-place reference trajectories, the utilization of piezoelectric actuators on the robot's arms and the consideration of the flexibility on the dynamic model of the system.

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