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Simplified approach for dynamics estimation of a minor mobility parallel robot

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ABSTRACT

This paper presents the identification of an approximated polynomial model for the dynamics of a parallel kinematics machine. The case study of a specific translational Cartesian manipulator is faced. Firstly, an analysis of robot dynamics is performed to verify the presence of poorly relevant terms. A polynomial simplified model is then built by fitting the actual behaviour of the robot prototype. The seek of the coefficients of the interpolating polynomials has been constrained taking advantage of robot peculiarities, such as symmetry and intrinsic properties of multibody systems dynamics. The effectiveness of the proposed simplification is then verified by comparison with robot behaviour.

1. Introduction

The dynamic modelling of robotic systems has been widely investigated in the last years. The importance of obtaining computationally efficient models, in fact, plays a fundamental role in the implementation of model based controls for which the computational burden strongly affects the effectiveness of the algorithm [1–3]. For this reason, the techniques that allow building simplified dynamic models arouse a particular interest, especially for complex multi-body systems. It is the case of Parallel Kinematics Machines (PKMs), i.e. those robots characterized by the presence of closed loop kinematics chains. On the one hand such peculiarity provides the PKMs with very interesting features of stiffness, accuracy and high dynamic capability. On the other hand it complicates the solution of the direct position kinematics, thus the computation of a symbolic dynamics model [4,5].

Almost all the mechanical principles have been used to carry on dynamic analysis of robotic systems, such as the generalized momentum approach [6], the Hamilton's principle [7], the Lagrange formulation [8–11], the virtual work principle [12–15] and Kane principle formulation [16,17]. The traditional Newton–Euler formulation, which has been widely used in the past [18,19] and is still used for specific tasks by some researchers [20,21], hardly adapts to the particular case of parallel kinematics machines.

In the recent past also many modelling methods have been investigated for the implementation of model based control schemes. Grotjahn et al. [22] first explored the possibility of splitting the effects of friction and robot dynamics on parallel robotic systems; the identification of such effects is performed in their work through the use of linear estimators, based on a mathematical model built by means of Jourdain's principle of virtual power, and a series of well structured experimentations. Li and Xu [23] approached the problem of modelling a minor mobility PKM with the virtual work principle, with the aim of implementing a simulated robust control. Wu et al. in [24] derived the dynamic model of a redundantly actuated PKM by using the virtual work principle, aiming at the design of a position-force switching control strategy. Even the Newton–Euler formulation has been used for control tasks: Wu et al. [25] used their well known simplified model [1] to experiment a zero phase error tracking control. Their simplification was carried on by specific simulations which allowed to separately consider the different terms of the dynamics model, similarly to what is experimentally done in the present work. These and many others have been the examples of dynamic control experiences on PKMs [26–30], denoting a significant and keen scientific interest on this topic.

The I.Ca.Ro. parallel robot (shown in Fig. 1a) is a pure translational Cartesian tripod owning to the 3-CPU class of parallel kinematics machines [31,32]; the robots of this class are characterized by three identical legs whose kinematic architecture is built of a cylindrical-prismatic-universal (C-P-U) joints chain (see Fig. 1b). The first body of each leg is connected to the robot chassis by means of a cylindrical joint, realized through a prismatic actuated pair and a revolute passive joint coaxial to the first one. The second body is linked to the first one through a prismatic joint,

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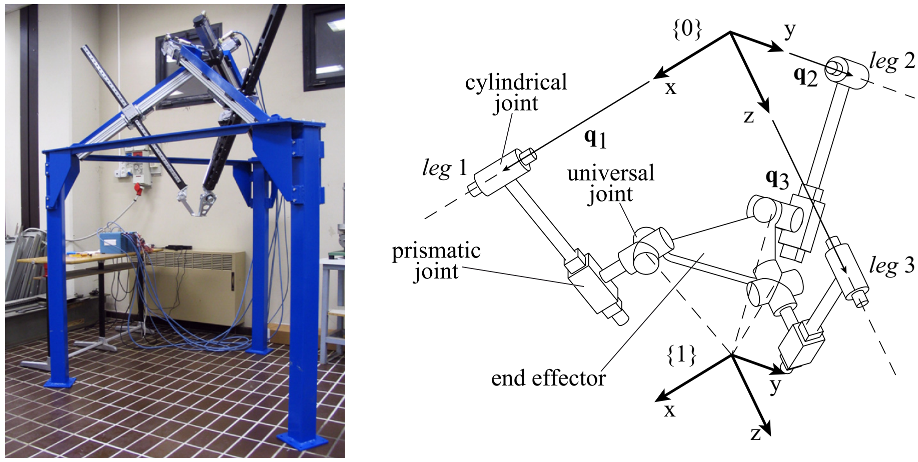

(a) (b)

Fig. 1. Prototype (a) and kinematics scheme (b) of the 3-CPU I.Ca.Ro. robot.

perpendicular to the axis of the cylindrical joint. At last, the second body is connected to the moving platform through a universal joint composed of two revolutes: the first revolute joint is parallel to the second link and the second is perpendicular to the first one. The last revolute of each leg connects the manipulator with the respective limb; the axes of such joints are coplanar. Because of the particular arrangement of the kinematic pairs within the robot legs, the end-effector owns 3-DOFs and is allowed to perform only motions of pure translation. Each leg is actuated by a brushless motor connected to a ball screw: the nut of such linear system provides the cylindrical pair of the leg with the needed translation.

An approximated approach to modelling of I.Ca.Ro. dynamics has been presented by Carbonari et al. in [33]. In their work the authors focused on the simplification of the dynamics model built by means of virtual work principle [34], aimed at the realization of a non-linear model based control scheme. The main goal of that work was to produce a numerically efficient model, suitable for control tasks. To this aim, a deep analysis was performed in order to point out the negligible terms present in the dynamics formulation; also, a simplified approach for computation of significant parts was proposed.

The present work is the natural continuation of author's research on the I.Ca.Ro. dynamics and shows how the dynamic behaviour of the Cartesian PKM I.Ca.Ro. can be estimated through an approximated approach. The main aim is here to provide an efficient and reliable model which can be used for real time computation of robot inverse dynamics; such tool can then be implemented in a model based control scheme for enhancement of robot performances. While the efficiency of the model is already discussed in [33], the reliability of the results has not been validated yet. In the remainder of the paper the simplification performed on the dynamics model are briefly described to legitimize the neglected contributions to dynamics. Then, the identification of the approximating functions is performed by means of properly designed experimentations. The paper also shows how it is possible to constrain the computation of such functions to reduce the effect of undesired phenomena on experimental data. At last, a comparison is proposed to validate the newly identified dynamics model.

2. Model analysis and simplification

In this section, the analysis of the I.Ca.Ro. dynamics is briefly summarized. As known, if no external force is applied to robot bodies and when the dissipative effects can be neglected, the dynamics equation of a mechanical system can be written as:

$$\boldsymbol{\tau} + \mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{V}(\mathbf{q},\dot{\mathbf{q}}) + \mathbf{G}(\mathbf{q}) = \mathbf{0} \tag{1}$$

where $\mathbf{M}(\mathbf{q})$ is the mass matrix, only dependent on system configuration, $\mathbf{V}(\mathbf{q},\dot{\mathbf{q}})$ is the vector collecting Coriolis and centrifugal forces that depends on both configuration and velocity of the mechanical system, while $\mathbf{G}(\mathbf{q})$ is the vector of the efforts deriving from the action of gravity accelerations on the bodies; $\boldsymbol{\tau}$ is a vector containing the forces exerted by the motors on the mechanical system; vectors $\mathbf{q},\dot{\mathbf{q}},\ddot{\mathbf{q}}$ respectively collect displacements, velocities and accelerations of the three actuated joints, i.e. the translational degree of freedom of the three cylindrical pairs. It is chosen to describe the system through such three translation to provide a direct correlation between the actuated variables and the configuration of the robot manipulator, despite the fact that such translations are realized by means of a ball screw commanded by a rotative motor. This choice is made for the sake clarity and it does not affect the results and the conclusions hereby shown.

The thrusts of the three motors, that should be intended as three forces acting on the direction of the respective cylindrical joints, can be expressed as $\boldsymbol{\tau} = \boldsymbol{\tau}_M + \boldsymbol{\tau}_V + \boldsymbol{\tau}_G$ where $\boldsymbol{\tau}_M = -\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}}$ is the vector collecting the inertial forces, $\boldsymbol{\tau}_V = -\mathbf{V}(\mathbf{q},\dot{\mathbf{q}})$ contains the thrusts due to centrifugal and Coriolis accelerations, while $\boldsymbol{\tau}_G = -\mathbf{G}(\mathbf{q})$ is the vector of forces given by gravity accelerations.

In [34,33], it is shown that the main contribution to the total efforts of the motors is due to gravity acceleration while inertial forces have a pretty low effect on the whole system, as well as Coriolis and centrifugal forces which are almost negligible when motors velocities and accelerations are low enough. Such observations allowed to reach a simplified formulation of robot dynamics through identification of the coefficients of proper approximating polynomials. The problem has been split in its sub-parts and inertial and Coriolis forces have been studied separately. The efforts due to gravity acceleration are not treated hereby since an efficient gravity compensation algorithm is already available for the I.Ca.Ro. controller.

The influence of $\boldsymbol{\tau}_M$ and $\boldsymbol{\tau}_V$ has been evaluated within robot workspace through the definition of the following influence parameters:

$$\begin{aligned} I_M(\mathbf{q},\dot{\mathbf{q}},\ddot{\mathbf{q}}) &= |\,\boldsymbol{\tau}_M\,| \,/\, |\,\boldsymbol{\tau}\,| \\ I_V(\mathbf{q},\dot{\mathbf{q}},\ddot{\mathbf{q}}) &= |\,\boldsymbol{\tau}_V\,| \,/\, |\,\boldsymbol{\tau}\,| \end{aligned} \tag{2}$$