Mechatronics 000 (2016) 1–15

Contents lists available at ScienceDirect

Mechatronics

journal homepage: www.elsevier.com/locate/mechatronics

Mechatronic modeling of a parallel kinematics multi-axial simulation table based on decoupling the actuators and manipulator dynamics

Constantino Roldán-Paraponiaris*, Francisco J. Campa, Oscar Altuzarra

Department of Mechanical Engineering, University of the Basque Country UPV-EHU, C Alameda Urquijo S/N, Bilbao 48013, Spain

ARTICLE INFO

Article history:
Received 26 July 2016
Revised 7 October 2016
Accepted 22 October 2016
Available online xxx

Keywords:
Dynamic modeling
Mechatronic model
Parallel mechanisms
Multi-axial simulation table

ABSTRACT

In this work a mechatronic model was developed for a parallel Multi-Axial Simulation Table (MAST) mechanism. The dynamics of the mechanism was obtained using the principle of energy equivalence and Boltzmann–Hamel equations. In this way, the procedure to obtain the explicit dynamic equations is simplified and has the advantage of being systematic. Also, the actuators and the control were modeled and integrated to simulate and study the system's positioning and torque.

A remarkable contribution of this work is that the mechatronic model developed considers the mechanism as a disturbance to the actuators in a decoupled manner, allowing to easily evaluate alternative designs of whether the actuators, the mechanism or both. Additionally, the procedure taken has been validated with experimental data from an actual MAST prototype.

1. Introduction

In the last twenty years, parallel kinematics machines have been increasingly used in several fields due to their high performance. For instance, hexapods and tripods are being used for scientific instrumentation due to their high precision positioning in several degrees of freedom [1]. Some solutions present a high stiffness-mass ratio and acceleration which makes them suitable for light machining tasks [2] in an industrial environment. Also, their capability of generating high accelerations makes them interesting for pick & place [3] or for generating harmonically complex motions with great bandwidth, as is the case of excitation tables [4].

Nevertheless, despite their increasing use, they are still complex machines to design, due to their kinematics, dynamics and control. That is why a mechatronic approach with model based design becomes essential for the conception of these machines. For that purpose, complex and detailed simulation tools capable of modeling the manipulator, drives and control dynamics in a cost efficient manner are required.

In that sense, a lot of effort has been putted into modeling the kinematics and dynamics for serial and parallel manipulators. Žlajpah [5] presents an overview of several computational tools (e.g. Matlab/Simulink, Dymola/Modelica) commonly used for simulations purposes focused on robotic systems. As for the dynamics, Lagrange and recursive Newton–Euler methods and the principle of virtual work are commonly employed to obtain the dynamic expressions for serial robotic mechanisms [6]. However, their applicability on parallel manipulators becomes a difficult task because of the kinematic constraints of the closed loops.

Previous works make use of multi-body models of the mechanism [7] or the forward dynamic problem in order to build a mechatronic model. In the first case, it can be justified when high loads are applied to the manipulator, because multibody models are capable of considering the flexible behavior of the machine components. Nevertheless, in that case, expensive software packages may be a limiting factor. On the other hand, with both approaches the contribution of the actuators to the global dynamics is often overlooked, modeling them as a simple inertia and thus assuming a rigid body behavior.

What is more, those formulations can't be used to introduce them in the control algorithm to perform a Compute torque control or a Feed-forward torque control. For that task, the inverse dynamic problem (IDP) has been traditionally used, as it provides the needed torques or forces in the actuators to perform the commanded motion. There are several works where the authors have used this approach to implement control schemes such as model-based control [8,9]. Codourey [10], developed a model-based control using the IDP to implement a feedforward control for a Delta robot. Similarly, Yang et al. [11] developed a computed force and

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* Corresponding author.
E-mail addresses: constantino.roldan@ehu.eus (C. Roldán-Paraponiaris), fran.campa@ehu.eus (F.J. Campa), oscar.altuzarra@ehu.eus (O. Altuzarra).

http://dx.doi.org/10.1016/j.mechatronics.2016.10.017

Please cite this article as: C. Roldán-Paraponiaris et al., Mechatronic modeling of a parallel kinematics multi-axial simulation table based on decoupling the actuators and manipulator dynamics, Mechatronics (2016), http://dx.doi.org/10.1016/j.mechatronics.2016.10.017

velocity control for a 6-DOF parallel mechanism also using the inverse dynamics.

Regarding the method to solve the IDP of parallel mechanisms, several formulations have been proposed in the past, as the Newton–Euler [12,13], the principle of virtual work [14] or Lagrangian methods [15]. Likewise, Lagrangian analysis is frequently employed for open-chains mechanisms. It's use in parallel mechanism yields in very large and often complex set of equations because of the kinematic constraints due to the closed loops of such systems. Also, an interesting approach with Newton–Euler has been taken in [13], where intermediate variables from the joint-space and matrix algebraic manipulation tools are used to obtain explicit dynamic models for a Gough–Stewart platform . In general, their applicability on parallel mechanisms is difficult due to the kinematic constraints caused by the closed loops [16]. As an alternative, with other methods of analytical mechanics (i.e. Boltzmann–Hamel equations, quasi-velocities and principle of energy equivalence [17]), the difficulty in finding a dynamic model suitable for computer simulations is greatly reduced.

Moreover, the common approach is to focus on the manipulator and then include the actuators. However, in several applications, especially when the payload and the manipulator are relatively light, the control cycle time or even the actuators dynamics can be more restrictive due to their finite stiffness, which limits the bandwidth and thus the dynamic performance of the machine in terms of speed, acceleration and trajectory tracking [18–20].

In the present work, a procedure for the mechatronic modeling of parallel kinematics machines is proposed, taking into account the rigid body dynamics of the manipulator, the compliant dynamics of the actuators and the cycle time of the control loops. The method is based on decoupling the dynamics of the actuators from the manipulator, in such a way that forces needed to move the manipulator are considered as a disturbance from the point of view of the actuators. This scope allows modeling the manipulator dynamics using the inverse dynamic problem, relating the motion of the actuators with the forces that generate the motion of the manipulator. To do so, although any method can be used, here it is proposed to use the Principle of energy equivalence and the Boltzmann–Hamel equations to compute the IDP. The actuators modeling and their transmission chain can be performed with great detail using a model of several degrees of freedom affected by the disturbance forces from the mechanism and the friction. Finally, the cycle time of the position, velocity and current control loops is taken into account. The whole model has been programmed in Matlab Simulink.

There are several advantages for this procedure. First, it is easy to evaluate alternative designs. Given the fact that models of control, actuators and manipulator are decoupled and represented by blocks, it is possible to replace them with new blocks representing alternative configurations. This reduces the time and effort required in the design and simulation stage for a given application yet being reliable. Second, it is possible to better evaluate the interaction between control, actuators and mechanism. For example, the bandwidth of the actuators alone vs. the bandwidth of the whole manipulator can be analyzed. Also, it is possible to isolate and evaluate the influence of the dynamic parameters of the manipulator or the actuator transmission chain on the tracking error. Simulation of the cycle time and its effect on the trajectory tracking and the driving forces allows also a better definition of the control specifications of the final prototype. Third, the use of the inverse dynamic problem results in an explicit set of equations that allows a fast computation comparing with multibody techniques and can be used also to improve the control algorithm if needed. Fourth, the use of the Principle of energy equivalence and the Boltzmann–Hamel equations allows for a more systematic and error free computation of the IDP for parallel mechanisms.

This article is organized as follows. First, in Section 2, the proposed procedure for mechatronic modeling of parallel kinematic machines will be detailed. Second, in Section 3, a case study based on a 3PRS mechanism will be given where the aforementioned procedures are employed. Third, the results of an experimental validation will be commented in Section 4. Finally, the main conclusions are presented.

2. Mechatronic modeling for parallel kinematic mechanisms

The method here proposed for the mechatronic modeling of parallel manipulators considers the actuators and the manipulator as two independent subsystems whose interaction is due to the Newton's third law. That is, from the actuators viewpoint, the mechanism generates some forces that work as a disturbance against their motion but, at the same time, those forces are the input that provides the manipulator's motion. That interaction is represented by F_i forces in Fig. 1 in a generic parallel manipulator. The result is that the actuators, which often times limit the overall system's performance, can be modeled in a more detailed fashion. On the other hand, to include the influence of the mechanism in the mechatronic model, the inverse dynamic problem (IDP) is solved, with the advantage that those equations can also be used in the control algorithm. Also, the control algorithm as in Fig. 2 and the cycle time of the closed loops has been considered due to their impact on the trajectory tracking, bandwidth and disturbance rejection. To the best of the authors knowledge, this approach that considers the mechanism as a disturbance for the actuators allows a deeper analysis of the interaction between control, actuators and mechanism and has not been addressed before.

2.1. Mechatronic model of the manipulator

In Fig. 1a mechatronic model of a manipulator is shown. It is assumed a joint space position control, where the control reacts to the position error measured in the actuated joints $\boldsymbol{\rho}$. This decision was taken since it is widely found in general industrial applications. However, more complex control algorithm can also be employed as will be shown in Section 2.3. In this way, the end platform position commands $\mathbf{x_0}$ are converted to the joint space through the inverse kinematic problem. Those $\mathbf{q}_{\rho_0}$ commands are then introduced into the mechatronic model of the actuators. As a result, the actuators reach a position $\mathbf{q}_\rho$ and the end platform location $\mathbf{x}$ is calculated with the direct kinematic problem. A rigid body behavior is here considered for the mechanism. To model the influence of the mechanism dynamics on the global behavior, the forces $\mathbf{t_p}$ generated to perform the motion are calculated with the IDP once actuators and platform motion are known. Those forces are then introduced as a disturbance into the actuators mechatronic model, in which a cascaded control in position, velocity and current is assumed. There, the mechanism forces are converted into a torque disturbance on the motor, thus acting as an opposition to the actuator.

2.2. Mechatronic model of the actuators

Regarding the actuator control model, a proportional position control with gain k_v is considered. If two encoders are used, a rotary one for the motor and a linear one for the actuator table, it is possible to control directly the linear position $\boldsymbol{\rho}$. The velocity and current control loops in Fig. 2 are based on a PI control, where k_p, k_i, k_{pc} and k_{ic} are the proportional and integral gains, respectively for each loop. Furthermore, their cycle times can be taken into account, sampling the signals and using the z-domain for the transfer functions of the system. Also, the response of the electrical part is modeled by taking into account the resistance R and inductance L

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