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Performance analysis and design of parallel kinematic machines using interval analysis

Carlos Viegas[a,*], David Daney[b], Mahmoud Tavakoli[a], Aníbal T. de Almeida[a]

[a] Institute of Systems and Robotics, University of Coimbra, Portugal
[b] INRIA, Bordeaux, France

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ABSTRACT

Some design methodologies for Parallel Kinematic Machines (PKM) have been proposed but with limitations regarding two main problems: how to improve multiple properties of different nature such as accuracy, force or singularity poses, and how to check these properties for all poses inside the PKM workspace. To address these problems, this work proposes to formulate the design problem as a feasibility problem and use a data representation which takes into account the uncertainty or variation of the involved parameters. This method, based on interval analysis, allows to evaluate several performance indexes of a PKM design. For validation purposes, this methodology is applied to a PKM, obtaining a continuous set of possible kinematic parameters values for its architecture which is capable of fulfilling several performance requirements over a desired workspace.

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1. Introduction

One setback of parallel machines is the fact that, for a fixed mechanical architecture, their properties or performance metrics are dependent on the dimensional geometry as well as their pose. This means that generally, these machines do not have constant behavior (in terms of accuracy, stiffness, and other properties) in their overall workspace. Another particular aspect of parallel machines is the existence of singular poses inside their workspace, resulting in loss or gain of degrees of freedom (DOF) and consequently loss of control of the machine. This effect can be mitigated within the PKM design process. Through this process of property evaluation and workspace characterization, one determines the values of the PKM kinematic parameters which will improve or certify the properties of the parallel machine.

The first approach consists of an optimization of a weighted criteria depending on the robot parameters, as it chooses the solution which offers the best compromise in terms of performance. Examples of this approach include Atlas approach [1,2], the cost function approach [3,4], dual expansion [5], compromise programming methodology [6], physical programming methodology [7] among others [8,9].

The second approach, on the other hand, defines the performance parameters in terms of constraints and not as subjects of optimization. It addresses the design problem in terms of feasibility, by determining a set of solutions for the kinematic parameters which ensure all performance requirements are met [10]. This approach has several advantages relative to design optimization as it is capable of dealing with manufacturing tolerances and other deviations from the nominal design

* Corresponding author.
E-mail addresses: carlosviegas@isr.uc.pt (C. Viegas), david.daney@inria.fr (D. Daney), mahmoud@isr.uc.pt (M. Tavakoli), adealmeida@isr.uc.pt (A.T. de Almeida).

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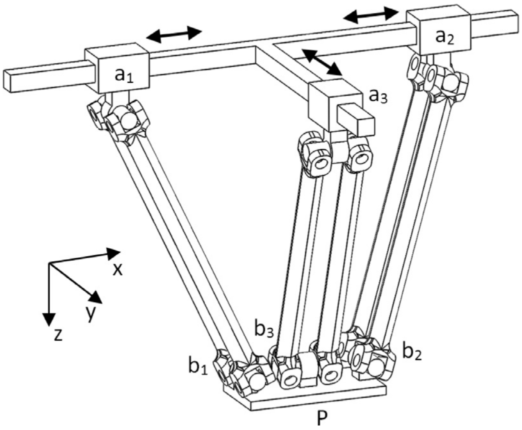

Fig. 1. Arrangement of the 3 P^UR limbs.

parameter values. It can also deal with a large number of different properties or design parameters which is something that optimization methods usually struggle with. Optimization methods may also converge to a single solution, which might or might not be global optimal, and depends on the weights given to the performance criteria considered or the compromises made between conflicting criteria.

The proposed design methodology in this work will focus on the second approach. The goal is to design a PKM which fulfills certain desired performance thresholds over its workspace. In other words, one want to obtain the set of kinematic parameters for a PKM with a desired workspace, characterized by its joint range limits, absence of singularities, with a desired motion accuracy and force properties. Other parameters such as the occurrence of link and platform collisions or PKM stiffness can be easily added to the model but are not subject to study in the present work. The workspace is the common variable and serves to unify the properties and certify the set of kinematic parameters.

Interval analysis [11–13] is used to evaluate the constraints and Branch-and-Prune to characterize the constraint workspace. Interval arithmetic, proposed by Moore [14], has been used for PKM property analysis, such as accuracy [15,16], sensitivity [17], force workspace [18], existence of singularities [19], among others. It deals with continuous intervals instead of discrete points, thus allowing a continuous evaluation of the entire workspace of the PKM as well as the entire range of its design parameters. The proposed design method is based on an algorithm which uses some well known interval analysis techniques. Some strategies employed to improve the efficiency of the algorithm are also presented and discussed. Some works have been made on parallel robot property analysis using constraints, Branch-and-Prune and interval analysis. In [20], a certified enclosure of the generalized aspects is computed. It is used to obtain connected sets of non-singular configurations for path planning of planar robots with 2 and 3 DOF, but in theory can be added additional constraints for any parallel robot case. In that work, arm and obstacle collision as well as joint limits constraints were demonstrated. However, few works have been made addressing the design of a PKM with certified performance. In [21] a robot with certified dynamic performance over a workspace is designed. As an example, a range of design parameters is determined, which ensure that a 2DOF robot with pre-selected actuators can perform a designated task, consisting on following trajectory with a specific velocity and acceleration. In [22], a method is proposed for synthesizing the largest tolerances in the model parameters of a PKM while keeping the pose error below a given limit. A similar work is done in [16]. Most works on PKM design either focus on less than 3-DOF PKM's or on a single property.

In this article, there is a first description of the proposed methodology for performance analysis and design of PKM's. Then, a case study of a spatial PKM design is introduced. The PKM used as a case study is a derivation of the well known Triglide spatial manipulator, proposed by Budde et al. [23], and is shown in Fig. 1. This architecture is chosen as it is a part of a larger system for factory automation over a large scale, being developed in the Institute of Systems and Robots of the University of Coimbra. However, the methodology presented here can be applied to any other parallel architecture.

Contribution and focus of this work include an efficient design methodology which addresses the evaluation of several PKM properties of different nature, including singular poses, joint limits, accuracy and force, for an entire workspace, while also taking into account possible variations or uncertainties of the geometrical parameters. Same methodology also enables design of a PKM with multiple DOF, taking into account different performance requirements. It is also the first part of a work on the design and realization of a real PKM with certified performance, so it is a self-contained thorough method which is validated with the physical realization of the PKM, shown in Fig. 12.

2. Design methodology

In this section, the interval analysis tool is introduced, with a detailed discussion on how it is used to evaluate each performance parameter. Then, the outline of the proposed design algorithm is presented.

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