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# Synthesis of partially decoupled multi-level manipulators with lower mobility

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ABSTRACT

The nonlinearity of the position equations of most parallel manipulators is one of the main disadvantages for the industrial application of this kind of mechanisms. In this paper, a systematic procedure for the type synthesis of lower mobility platforms, characterized by partially decoupled equation sets in their position problem, is presented. The approach proposed consists in obtaining them using a multi-level serial morphology, in which each level is attached to the base in parallel by some limbs. The aim is to design manipulators with simpler limbs by distributing in different levels the contributions to obtain a motion pattern with translational and rotational degrees of freedom (DOF). Out of many possibilities to obtain 4 and 5 DOF parallel manipulators, three cases with a partially decoupled position problem are analyzed. Finally, a case study and a prototype of a double-platform 4 DOF manipulator with Schönflies' motion is presented.



## 1. Introduction

The advantages that parallel manipulators have over serial robots in terms of accuracy, and load-to-weight ratio make them suitable for industrial applications where all these characteristics were needed. However, the expectations generated by these manipulators have not been fulfilled. In some cases because of an inappropriate choice of the manipulator, not focused on the application where it was to be employed. But in general terms, their disadvantages (i.e. a complex resolution of the position problems that burdened their control, their reduced workspaces, and their higher mechanical complexity) exceeded the foregoing advantages.

The first stage on the design of a new architecture of a parallel manipulator is the definition of the motion requirements. This point must be focused on the industrial applications where it will be used. Though it is true that a 6 DOF manipulator has the advantage to maneuver around singularities avoiding link interference, this is so at the cost of a more complicated mechanical assembly and a more complex actuation system. There is a huge variety of applications where it is not necessary to use 6 DOF manipulators (i.e. translational parallel manipulators for automation and pick and place, or spherical parallel manipulators for orientation devices, or a great number of tasks that require 4 or 5 DOF, such as automated assembly and five-axis machining).

In this scope of applications is where the concept of lower mobility [1] or limited DOF [2] parallel manipulators appears. Their analysis and design are, in general, of higher complexity than that of 6 DOF manipulators and they require a greater effort in the initial stages of design. It is essential a careful type synthesis that provides the motion pattern needed with a simple solution of the kinematic problems. In this regard, it is important to obtain platforms with decoupled position equations. For example, Gosselin and Kong [3] obtained several 3 DOF translational platforms that were input–output (I/O)

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decoupled. If not decoupled at least they should be partially decoupled; this means that some of the equations will be decoupled while the rest of them will be easily solved without the need of numerical methods. Nevertheless, decoupled mechanisms are not free of disadvantages as they can present lower stiffness and large elastic deformations that should be taken care of.

The methods used for type synthesis are commonly based on the Screw Theory, the Theory of Groups of Displacements or the Theory of Linear Transformations. In [4,5] various methods for type synthesis are compiled presenting many solutions of lower mobility parallel manipulators with partially decoupled motions with 4 and 5 DOF. Screw theory [6] has been used for the synthesis of spherical manipulators in [7,8], translational parallel manipulators in [9,10], or four DOF manipulators in [11,12]. Designers can also resort to the Theory of Groups of Displacements, which applies the Lie Group structure of the set of spatial rigid body displacements [13–15]. This approach provides a conceptual treatment of the way in which the motion pattern needed is generated allowing the synthesis of the corresponding manipulator as in [16,17].

Specific search of symmetrical parallel manipulators is compiled in [18,19]. The use of lower mobility parallel manipulators based on articulated traveling plates for industrial applications of pick and place tasks is discussed in [20]. Finally, the Theory of Linear Transformations has been used for the finding of fully isotropic lower mobility parallel manipulators with four DOF in [21] and five DOF in [22], and maximally regular parallel manipulators of five DOF in [23].

This paper introduces a new approach to obtain lower mobility platforms based on a multi-level morphology. Each level is composed by a moving platform with a parallel connection to the base. These levels are inter-joined by kinematic pairs, and this assembly provides the end-effector's level with the desired motion. The multi-level morphology proposed in this paper relies on the following basis. A motion pattern involving translational and rotational DOF often requires complex limb structures. If we could distribute the contributions to the desired final motion pattern in several stages, we could use simpler kinematic chains allowing the position control in a distributed way. The assembly of the different levels conforming the manipulator is analyzed using the mathematical concepts in the Theory of Groups of Displacements [24]. If the Groups of Displacement are used, the finite displacements could be accounted offering an intuitive description of the motion type in each level.

In this paper, first the seminal ideas of this new concept are described, and the type synthesis is presented in order to look for the different ways of obtaining lower mobility manipulators with four and five DOF. From all those possibilities, some cases are chosen to show how limbs must be used and how the different levels of the manipulator must be assembled in order to get a partially decoupled position problem. Finally, a case study of a manipulator with 4 DOF and Schönflies' motion is presented.

## 2. The multi-level morphology

The Type Synthesis of parallel manipulators consists in finding all the possible types of kinematic chains that can constitute the limbs of a manipulator with a desired motion of the mobile platform (MP). Each of those kinematic chains should be a generator of motion that once assembled to the MP can produce the motion pattern required. The traditional process followed for this type synthesis is aimed at finding symmetrical morphologies, but it could also be directed to obtain all possible combinations of such kinematic chains.

In this point it is necessary to mention that we resort to the Theory of Groups of Displacements [13] because it is an appropriate mathematical tool for the analysis of finite motion and the type synthesis. In this theory, the group algebraic properties of the set of rigid-body motions are applied. On the one hand, the displacement set of a serial chain is modeled by an $n$-dimensional subset of displacements, sometimes belonging to a subgroup of displacements, using a product of $n$ subsets, often subgroups. On the other hand, the displacement set obtained from the parallel assembly of several displacement subsets is derived by the intersection of these latter.

The multi-level morphology proposed in this paper relies on the following basis. A motion pattern that involves displacement subsets with the translational subgroup $\mathcal{T}_3$[1] and some rotation, is often a displacement subset that requires mechanically complex motion-generators. If we could distribute the contributions to that final motion pattern in several stages we could use simple kinematic chains. And besides, if these can control the final motion in a distributed way, then the position analysis could be more effective.

In order to do that, we have figured out a multi-level morphology for manipulators as illustrated in Fig. 1. The manipulator has a main articulated chain with the MP and several platforms at levels, and it constitutes its backbone. The tool is attached to the MP and has the motion pattern required, while lower levels are joined by lower kinematic pairs and have displacement subsets of lower dimension. The $n$ kinematic chains required to join the manipulator to the base in parallel are distributed among the several levels. In doing so we have to try to produce a simple position problem, and that the efforts applied are evenly distributed. In some way, this concept could be understood as a parallel assembly of parallel manipulators [25].

Using the Group Theory to analyze the motion obtained, we can follow the reasoning below. The displacement set of the lowest level of the robot will be determined by the intersection of the motion generators of the kinematic chains that join it to the base. When this level is joined with the following level, a product of the displacement set of the lowest level and the

[1] See Appendix for Nomenclature of Displacement Subgroups.