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## CERTIFIED KINEMATIC TOOLS FOR THE DESIGN AND CONTROL OF PARALLEL ROBOTS

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### 1 MOTIVATIONS

Parallel robots [1, 2] are closed-loop kinematic manipulators usually with two platforms (a base and an upper platform as the end-effector) that are linked by multiple kinematic chains. Each kinematic chain has joints that are either actuated (active joints) or not (passive joints) and the consecutive joints are linked by a body. Such an architecture bestows numerous advantages: these mechanisms are best known for presenting interesting performances in terms of dynamics, stiffness and accuracy. Moreover, most of the parallel robots are actuated at their base (the other joints being usually passive). As a result, many parts of such robots are subject to traction or compression constraints [3] making it possible to use less powerful actuators and reduce the mass of the movable links, unlike their serial counterparts. Although parallel robots are less spread than the serial ones, they are gaining interest over the last decades in several domains: from the food industry for pick-and-place applications [4] (*e.g.* the Adept Quattro 4-DOF Delta robot) to the medical world (*e.g.* the SurgiScope 4-DOF Delta robot), through the simulated environments (*e.g.* the Rexroth 6-DOF hexapod dedicated to flight motion simulation). Moreover, other potential applications arise such as the inertial stabilization [5] of cameras [6] or sighting devices in the naval environment [7].

Despite all the before-mentioned advantages of parallel robots, the latter are also well-known for being complex systems: numerous historical challenges arose regarding these architectures, namely solving the Forward Kinematic Problem (finding the coordinates of the end-effector upper platform given the joint values) while determining the singularity loci to avoid and taking into account the effects of uncertainties on the design parameters of the closed-loop robots as well as on their control (measurement errors).

### 2 CONTENTS

This paper aims to present a methodology related to the design and the control of parallel robots. Its challenge is twofold. On the one hand, one focuses on the problematics of design. In particular, given a parallel mechanism defined by its design parameters and its kinematic modelling as well as its targeted application (prescribed workspace), the idea is to certify the absence of any numerical instabilities (computational and physical singularities) that may jeopardize the integrity of the robot. Such a work is called certification of the (Inverse and Forward) Kinematics of the robot and will be treated through two different but complementary approaches:

- the first one being global involving *symbolic* computation and formal calculus (elimination of variables, computation of the discriminant variety [8] w.r.t. the projection onto the parameter space) that can sometimes be difficult to compute due to the complexity of the robot of interest;
- the other one being rather local using *continuation* methods [9] coupled with *multiple-precision interval arithmetic* [10] (using the Kantorovich unicity operator [11]) that may be used for real-time applications.

The strength of this methodology relies on the appropriate combination of both techniques enabling the certification of a larger range of parallel robots. After exposing the theoretical concepts behind this methodology of certification, the latter will be applied to some examples of real-case parallel robots.

On the other hand, this paper also presents a strategy to control parallel robots, especially ensuring that the robot never leaves the certified workspace through a software joint velocity limitation algorithm. This strategy introduced in [12] will be detailed and applied to a special class of parallel robots: Spherical Parallel Manipulators (SPM) [13, 14] with coaxial input shafts (CoSPM) [15].

The paper will be organized into two main parts and as follows:

- *Tools for the Design.* A first section recalls the basic notions required for the kinematic analysis of parallel robots as well as the existing methods and tools used by roboticists to investigate the latter. A second section exposes some certified kinematic tools and the mathematical background behind them. Some study cases on various parallel robots (*e.g.* 3-DOF tripod [16], 3-DOF SPMs [13, 15], hexapod [17]) will be given in a third section.
- *Tools for the Control.* A forth section explaining a strategy to secure the control a special case of parallel robots, Spherical Parallel Manipulators with coaxial input shafts (CoSPM) so that the robot of interest never leaves the safe regions delimited by the tools previously introduced. Results can however be generalized to other parallel manipulators.

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