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Reconfigurable mass parameters to cross direct kinematic singularities in parallel manipulators

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ABSTRACT

Some authors have suggested the concept of adding active masses to some links so as to allow us to control the location of their center of mass and other dynamic properties for serial manipulators. This paper investigates the possibility of following a desired trajectory that contains direct kinematic singularity configurations using reconfigurable mass parameters in parallel manipulators. To illustrate the concept, an actuated mass is added to each of the two branches of a 2-R$\underline{\text{P}}$R planar parallel manipulator. The dynamic model of this manipulator is developed using the principle of virtual work. The model is then used to compute the required displacements, velocities and accelerations of the active masses over time as to allow the manipulator to successfully cross singular configurations. Numerical examples are presented to support the idea.

1. Introduction

Trajectory planning for robotic manipulators deals with finding a path between the initial and final positions of the end-effector. Unlike serial manipulators, parallel mechanisms may have many singular configurations inside the workspace which often complicates planning trajectories to deal with these singularities. Many path planning algorithms have been developed to deal with singular configurations. Most research on path planning for parallel manipulators has been focusing on singularity avoidance. Dasgupta and Mruthyunjaya presented a path planing algorithm for the Stewart-Gough parallel manipulator where the algorithm is used to design a singularity-free path between the desired initial and final end-effector positions [1]. This path planning algorithm provides the shortest path while it guarantees that all the points of the trajectory are well-conditioned. To deal with the complexity of the problem, a sequence of convenient and non-singular via points is defined. Dash et al. used a numerical method for singularity-free path planning where all singular points inside the workspace are determined and grouped as clusters of singularities [2]. Then, every cluster is estimated as a polyhedron obstacle. Finally, an obstacle avoidance algorithm is applied to avoid these polyhedral objects. Li et al. introduced a method to obtain a continuous singularity-free 6-D workspace for the Stewart-Gough platform [3]. First, an analytical solution is applied to obtain the singularity locus of the Stewart-Gough platform. Then, the largest singularity-free hyper-sphere is obtained for a given position (center pose). For this purpose, an optimization problem is defined to find the closest point on the singularity manifold to the center point. Khoukhi et al. applied a multi-objective optimization method to design a robot trajectory considering the robot's kinematics and its dynamic model [4]. The presented algorithm minimizes time and the necessary energy to achieve a trajectory between initial and final end effector poses while avoiding singular configurations through maximizing a measure of manipulability. Sen et al. constructed a Lagrangian function which consists of two terms analogous to kinetic energy and potential energy [5]. The kinetic energy term tends to keep the trajectory short while the potential energy term (also known as penalty

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function) forces the path to remain inside the workspace as well as avoiding the singular configurations. Chen and Liao defined a hybrid optimization algorithm to minimize travel time and the total energy consumption of the manipulator where the maximum torque is constrained [6]. Consequently, the singular configuration will be eliminated from the workspace since the torque at singular configurations increases dramatically. Lin et al. presented an evolutionary optimization algorithm for path planning which keeps the singular points as far as possible from robot's trajectory [7].

These works focus on singularity avoidance where the workspace shrinks and the complexity of the path planning algorithm increases [1–7]. Instead of avoiding the singularities, it is proposed here to use the concept of reconfigurable mass parameters to generate inertial forces that allow a manipulator to follow paths that contain singular configurations thus allowing one to maintain the original workspace volume.

Briot and Arakelian analyzed the forces and moments that are applied on the end-effector by the legs and external forces when passing through a singularity [8]. They proposed that if the work of the forces along the uncontrollable direction is equal to zero at a singular configuration, then the end-effector can pass through singular configurations. They applied this concept on the dynamic model of a parallel manipulator and found the necessary condition. This condition appears as a constraint on the velocity and acceleration of the end-effector along the trajectory. In other words, they designed a path between an initial and final position with a specific velocity and acceleration profile. Then, the obtained velocity and acceleration profile will generate specific inertial force and inertial moment profiles which result in satisfying the earlier condition. This method considers the dynamics of parallel manipulators at singular configurations. However, it does not consider the neighborhood of singular configurations where controlling the parallel manipulator is also difficult.

Redundancy in parallel manipulators is normally divided into actuation redundancy, branch redundancy and kinematic redundancy [9–13]. Actuation redundancy consists of replacing passive joints with active ones [10,14–16] where the number of degrees-of-freedom or mobility of the manipulator does not change. Although actuation redundancy can help either eliminate or reduce singular configurations, issues such as force interference make the manipulators more complex to analyze, design and control [17,18]. The second type of redundancy is called branch redundancy where an extra actuated branch is added to the manipulator [19]. Branch redundancy can improve the force capabilities of the manipulator and reduce the number of singular configurations. The third type of redundancy is called kinematic redundancy where active joints and links are added to one or more branches of the manipulator [11,20]. This type of redundancy can enhance the dexterity of the manipulator as well as enlarge its workspace. Additionally, kinematic redundancy allows one to follow trajectories choosing configurations that are far from singular configurations since the inverse displacement problem has an infinite number of solutions [21].

Although actuation and kinematic redundancy may help the manipulator to follow trajectories with singular configurations, the number of active joints is greater than the DOF of the manipulator along the trajectory. This increases the complexity of the control scheme of the manipulator. However, the number of active joints of a manipulator with reconfigurable mass parameters is equal to the DOF of the manipulator in most of trajectory. This will be explained later in this paper.

A new type of redundancy that the authors called internal redundancy has been the focus of some attention in the context of serial manipulators [22]. Similar to the types of redundancy described earlier, a new set of degrees of freedom (DOF) is added to the serial manipulator. However, in contrast with the redundant actuators and/or links described earlier, the new DOF is used to change the internal geometry of a link resulting in the change of the location of the link's center of mass and its inertial mass distribution parameters (i.e., its mass moment of inertia). Since the changes are made within the internal members of the link, the redundant DOF does not have a direct effect on the end effector pose (i.e., position and orientation) or the manipulator's workspace.

The authors have applied the concept of reconfigurable mass parameters to improve the dynamic parameters of the 3-$\underline{R}$RR planar parallel manipulator while performing tasks with sharp corners [23–25]. This paper, on the other hand, focuses on using reconfigurable mass parameters to produce inertial forces to allow a manipulator to follow trajectories with singular configurations.

The idea of using active masses to produce inertial forces and moments has also been recently proposed by Gosselin et al. [26]. They simulated a 1-DOF inertia generator device where an internal active mass is moved in response to the external acceleration that is applied to the system. The theoretical results suggest that limited inertia force can be generated to modify the effective inertia of the device. Also, they built a prototype where the experimental results confirm that the prescribed inertia forces are generally well generated. They also expanded the simulation where four active masses were mounted on a 3-DOF platform to generate inertial forces and moments in a plane. Similarly to the 1-DOF device, it was shown that a prescribed translational and rotational inertia can be generated through strategically moving the masses.

Adding actuated masses has also been proposed for dynamic balancing. Wijk and Herder introduced the Active Dynamic Balancing Unit (ADBU) method to dynamically balance a mechanism [27]. In this method, a balancing unit with separate actuators is added to the mechanism. The number of actuators is equal to the DOF of the mechanism and every actuator carries a mass. A control system is applied to actively control the spare actuators to balance the dynamic forces and moments of the mechanism. Also, it was suggested that the balancing unit can be applied for handling variable payloads.

In the literature, the disadvantages of the additional masses for dynamically balanced mechanisms have been discussed [28,29]. The main disadvantage is considered as the inertia added to the system due to the extra masses and actuators. On the other hand, the advantages of dynamically balanced mechanisms are a reduction in wear, fatigue and noise as well as an increase in accuracy [28,30].

In this paper, the concept of reconfigurable mass parameters is applied to a planar parallel manipulator. First, a 2-R$\underline{P}$R manipulator with active masses in both branches is described and its kinematic and dynamic equations are derived (Section 2). Then, the implementation of reconfigurable mass parameters and the algorithm that is applied in this work are explained (Section 3). The architectural parameters and trajectory planning algorithm are explained through a numerical example in Section 4 and then discussed in more detail in Section 5. Finally, Section 6 presents the conclusions and briefly discusses potential future work.