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On the dynamic performance of parallel kinematic manipulators with actuation and kinematic redundancies

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ABSTRACT

The performance of parallel kinematic manipulators may be enhanced by the use of actuation and kinematic redundancies since they promote a significant reduction in the singularities and homogenization on the actuation forces. Considering these facts, this manuscript proposes a strategy to assess if the use of one or more actuation/kinematic redundancies can be good alternatives to improve the dynamic performance of a planar parallel kinematic manipulator. This may not be a trivial task since their dynamic performance can be highly dependent on which trajectory is performed and how the redundancy is treated. To overcome the former issue, a dynamic index depicted in the system workspace is proposed. To overcome the latter issue, different optimization strategies to treat actuation and kinematic redundancies are compared. From numerical results, one can conclude that the dynamic performance of the manipulator can only be enhanced if the redundancies are treated accordingly. Moreover, the benefits of redundancy are highly dependent on the chosen trajectory, the end effector's position and orientation.

1. Introduction

It is well-known that parallel kinematic machines (PKMs) are capable of providing precision, high stiffness, good dynamic performance and load capability. Although being a promising alternative to industrial manipulators, PKMs may suffer from the presence of singularities in their workspace [1,2]. As a result, the ratio between the useful working space and physical space occupied by the equipment is rather low, which is an important drawback. Some authors, e.g. [3–7], have suggested that the use of redundancy can be a good alternative for minimizing the presence of singularities enhancing the workspace usability. Moreover, the addition of redundancy might also provide higher accuracy [3], better movements and forces' transmissibility [8], improved dynamic performance [9–12], enhanced energy efficiency [13], among others.

In this manuscript, two distinct kinds of redundancies are exploited: actuation and kinematic redundancies. Actuation redundancy can be implemented by the actuation of passive joints or by the inclusion of active kinematic chains [14]. The degrees-of-freedom (DOFs) of the end effector's manipulator are kept constant in both strategies. In spite of possessing more actuators than DOFs, the kinematic description of a manipulator with actuation redundancy is unique. In order words, the inverse kinematic problem presents a single solution. On the other hand, kinematic redundancy can be implemented by the introduction of extra active joints in a kinematic chain. The inverse kinematic problem presents infinite solutions, i.e. there

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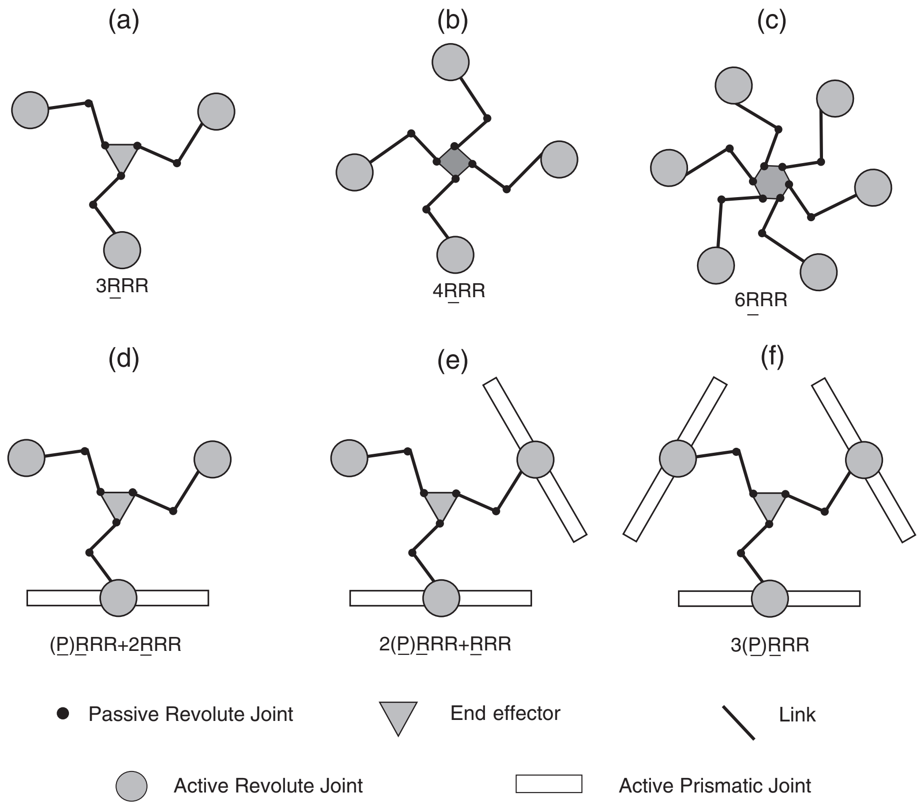

Fig. 1. Non-redundant and redundant manipulators: (a) 3RRR, (b) 4RRR, (c) 6RRR, (d) PRRR + 2RRR, (e) 2PRRR + RRR and (f) 3PRRR.

are infinite possible joint parameters for a single end effector's pose (rotation and position). According to [14], kinematically redundant PKMs provide higher mobility than required for the task allowing for the avoidance of singularities and obstacles.

Regarding actuation redundancy, several authors have claimed that this strategy may enhance the performance of PKMs. In [15], the contribution of actuation redundancies to enhance the dynamic performance of pick-and-place robotic systems have been exploited. In order to do that, two dynamic indexes based on the maximum end effector's acceleration have been proposed. The authors have concluded that the considered redundancy is capable of homogenizing the required torques/forces enhancing the dynamic performance of such manipulators. In [11,16], kinematic and dynamic models of the 2RRR, 3RRR and 4RRR PKMs (see Fig. 1) have been described. It could be concluded that the redundant manipulators have presented not only better conditioning, payload and stiffness performances but also better dynamic response. In an industrial application, the authors of [17] have concluded that the performance of a redundant parallel tool head leads to notable advantages over the non-redundant one, including enlarged singularity-free workspace, improved dexterity performance, and higher stiffness. Recently, a measure for evaluating the dynamic performance of parallel manipulators with a single actuation redundancy has been proposed by [18].

Regarding kinematic redundancy, reports exploiting the reconfiguration capabilities of this strategy can be found. Among them, [3,19–21] have compared numerically and experimentally the performance of non-redundant and redundant manipulators. The main objective of these works has been to obtain enlarged workspace with an acceptable precision and free of singularities. The results have shown that the redundant manipulator is capable to reconfigure itself avoiding singularities and increasing the useful workspace. The work of [5] has presented a manipulator with three levels of kinematic redundancy called 3PRRR. An optimization strategy has been proposed and applied to avoid the singularities of the manipulator. The comparison between the redundant and non-redundant manipulator has shown that redundancy is capable of avoiding the singularities and increasing the workspace. Recently, [22] has described optimization strategies to deal with kinematic redundancies. Different trajectories have been exploited demonstrating that the redundant manipulator is capable of overcoming the issues with singularities.

The comparison between the dynamic performance of non-redundant and redundant manipulators is highly dependent on the selected trajectory. This is an important drawback since a fully understanding of the redundancy capability cannot be assessed. The authors of [23] have proposed a novel dynamic performance index that combines the acceleration, velocity, and gravity terms of the dynamic equations. This index can be directly employed to the performance assessment of manipulators with actuation redundancy. Due to the reconfiguration capabilities of the kinematically redundant manipulators, the same index cannot be directly exploited. Considering these facts, this manuscript proposes a strategy to assess if the use of one or more