Mechanism and Machine Theory 77 (2014) 92–110

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmt

Design and analysis of reconfigurable parallel robots with enhanced stiffness

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ARTICLE INFO

Article history:
Received 16 July 2013
Received in revised form 29 January 2014
Accepted 7 February 2014
Available online 12 March 2014

Keywords:
Reconfigurable robots
Parallel kinematic manipulators
Kinetostatics
Static redundancy
Under-actuation
Virtual alternating constraints
Variable topology

ABSTRACT

Static redundancy in a parallel manipulator can enhance the stiffness of the end-effector, improve its fault tolerance, minimize its singularity loci, and reduce the internal loads experienced by the joints. Traditionally, this form of redundancy would be accompanied by actuation redundancy. Introduced in this paper is a new approach to statically enhance a manipulator without actuation redundancy. This is achieved through the use of lockable passive joints that are utilized in an alternating fashion to reconfigure the system into various isostatic and hyperstatic topologies without any external assistance. Although applicable to both kinematically non-redundant and constrained manipulators, this approach is especially effective for those with lower instantaneous mobility. The inherent redundancy in these reconfigurable robots is exploited to obtain full finite mobility with as few as one actuator through under-actuation with the use of virtual alternating constraints. The architecture design, kinematic analysis, and kinetostatic analysis of the proposed robots are addressed herein, followed by a case-study to demonstrate the effectiveness of the proposed design and analysis.

1. Introduction

Reconfigurable parallel robots have attracted considerable interest both in the areas of machine design and motion control over the past two decades. Traditionally, the objective for reconfigurability has been the alteration of mobility [1,2], or motion characteristics [3,4]. However, with the exception of a few [4,5], reconfigurability for enhanced stiffness or static redundancy has not been extensively studied.

Reconfigurability in parallel kinematic manipulators (PKMs) can be classified into geometric, topological, or a combination of the two [6]. Geometric morphing deals with the variation in size or orientation of the branches that make up the manipulator, without altering its kinematic architecture. For examples of geometric morphing see [4,5]. Topological morphing deals with variations in the kinematic architecture of the manipulator by changing the types or the sequence of the joints that make up the system. For examples of topological morphing see [1,2,7].

Analogous to the geometric and topological classifications of reconfigurability, the variation in the static and stiffness characteristics of a PKM can also be classified into similar groups (see Fig. 1). In this context, the geometric approach will take advantage of the change in the size and orientation of the branches to alter the stiffness of the end-effector or the internal loads experienced by the members, whereas the topological approach will utilize alterations in the connectivity of branches and joint types to do the same. Generally, only the topological approach has the potential to generate a statically redundant system, which makes it more suitable for autonomous and aerospace applications.

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http://dx.doi.org/10.1016/j.mechmachtheory.2014.02.005
0094-114X/

Nomenclature

$\mathbf{b}$	base vector
C	branch connectivity
d	Cartesian motion parameter
$\mathbf{h}$	module position vector
$\mathbf{F}$	external load vector
$\mathbf{f}$	internal load vector
f	number of relative degrees of freedom
$\mathbf{J}$	Jacobian matrix
$\mathbf{K}$	stiffness matrix
k	limb stiffness
M	mobility
N	summation scalar
n	number of load-bearing limbs
$\mathbf{p}$	platform vector
$\mathbf{Q}_P$	vector of lengths for the locked passive members
$\mathbf{q}$	limb vector
q	limb length
$\mathbf{R}$	rotation matrix
U	strain energy
$\mathbf{X}$	module pose vector
$\mathbf{X}_D$	vector of dependent Cartesian parameters
$\mathbf{X}_I$	vector of independent Cartesian parameters
θ	rotation angle

Subscripts

A	related to the actuated member
C	related to the Cartesian space
hyp	hyperstatic
iso	isostatic
J/j	related to the joint or the joint space
l	link
P	related to the passive member
x	along/about x-axis
y	along/about y-axis
z	along/about z-axis

Traditionally, in lower mobility manipulators, the topology is designed to accommodate the motion requirements. The static and stiffness characteristics are then addressed by altering the geometric parameters such as joint locations or the sizing of the actuators. By separating the kinematic and the static requirements, one can design manipulators with lower mobility and rather attractive static traits. Such lower mobility systems can exhibit stiffness characteristics comparable to that of a PKM with full mobility and superior to conventional lower mobility manipulators with permanently constraining legs.

In addition to applications where varying the topology can enhance the static and stiffness characteristics of a PKM in motion, there exist applications where a manipulator may be required to act as a structure for a significant period of time during which it will be experiencing external loads far greater than those required for actuation. One example would be a PKM belonging to an autonomously reconfigurable structure. Although the manipulator may be in a stationary pose, any shift in the position of its payload, which may happen to be another PKM, could induce large internal loads on the manipulator. Another example is a PKM which would be experiencing large dynamic loads as it would be autonomously transported to reconfigure a larger structure. In any of these cases having a manipulator that can exhibit enhanced static and stiffness characteristics is desirable. Traditionally, this enhancement comes at the cost of having more actuators than kinematically required.

In this paper we introduce a family of reconfigurable parallel robots with enhanced static characteristics with only as many actuators as the required instantaneous mobility. These robots belong to the topologically reconfigurable category. Although the focus in this paper is on robots with lower instantaneous mobility, the presented design and analysis methodologies are also applicable to enhance those with full mobility such as the Gough–Stewart parallel manipulators [8,9]. The proposed reconfigurable robots are fault tolerant and can provide enhanced static and stiffness characteristics with minimal number of