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Modular design of parallel robots with static redundancy

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ABSTRACT

Modularity in design for most mechanical systems can lead to higher reliability and reduction in cost for the design and build of the system. In this paper, the modular design of a new class of reconfigurable parallel robots is discussed. These robots can attain static redundancy without actuation redundancy and are ideal for applications that require fault tolerance and enhanced stiffness but may not necessarily require redundant actuation. Such applications can be found in the area of wing morphing for performance improvement. It is shown that a universal modular limb connectivity type exists that can be adopted for modular design of statically redundant parallel robots, regardless of the degree of static redundancy of the system. Additionally, the modular design approach is demonstrated through a case study for a morphing wing application.

1. Introduction

There are robotic applications that lend themselves well to the usage of less conventional approaches in robot design, specifically, where the finite pose of the end-effector may be of interest as opposed to the instantaneous one. *Finite* pose/degrees of freedom (DOFs) are the minimum number of geometric parameters required to uniquely identify the pose of a rigid body in space, i.e. three for planar and six for spatial cases, whereas *instantaneous* DOFs are those of a rigid body whose velocities and accelerations could be controlled [1]. For fully actuated parallel kinematic manipulators (PKMs), such as the Gough–Stewart [2,3] family of PKMs, the independent finite and the instantaneous DOFs are the same. However, if the system is under-actuated,[1] one could have more independent finite DOFs than instantaneous ones. The finite and instantaneous mobilities of the manipulator could then be defined by the achievable independent DOFs in either case.

Some examples of less conventional approaches to realize this type of under-actuation can be found in [4], in which the authors used locks to remove the DOFs associated with certain passive joints in order to under-actuate a serial robot, or in [5], in which the authors used a guiding rack with a specific motion sequence to obtain full finite mobility with one actuator for a parallel robot. For the most part, the added efficiency in such cases comes at the cost of more complex control and motion planning algorithms, as well as topological constraints to accommodate the under-actuation.

Similarly, the authors in [6] introduced a novel family of reconfigurable robots that can modify their topology to alter their stiffness and static characteristics. These robots, referred to as parallel robot(s) with enhanced stiffness (PRES), have applications in the aerospace field [7].

After a brief introduction of PRES's (Section 2), their modular design will be investigated (Section 3). Thereafter, the results will be discussed (Section 4), and a case study will be presented (Section 5). The results will clearly identify the architecture requirements for

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[1] Under-actuation in the context of present application only deals with holonomically constrained systems.

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Nomenclature

C	branch connectivity
d	Cartesian motion parameter
$\mathbf{F}$	external load vector
$\mathbf{f}$	internal load vector
f	joint force/torque
$\mathbf{J}$	Jacobian matrix
$\mathbf{K}$	stiffness matrix
k	limb stiffness
M	mobility
N	summation scalar
N_l	number of links
N_j	number of joints
r	degree of static redundancy
λ	number of links per limb
ϕ_i	degrees of relative motion permitted by joint i

Subscripts

A	related to an actuated limb/member
C	related to the Cartesian space
hyp	related to the hyperstatic state
I/iso	related to the isostatic state
J	related to a joint or the joint space
l	related to the locked state
P	related to a passive limb/member
R	related to the redundant portion of the system
u	related to the unlocked state

Superscripts

A	related to an actuated joint/member
hyp	related to the hyperstatic state
iso	related to the isostatic state
PL	related to a lockable passive joint/member
PR	related to a regular passive joint/member

achieving a modular design. The case study will demonstrate the implementation of the modular design for a wing morphing application.

2. Parallel robots with enhanced stiffness (PRES)

The family of robots presented in [6] enjoys enhanced stiffness and static characteristics without actuation redundancy. These robots have the ability to alter their topology using a series of lockable passive joints. This allows the PRES to achieve an array of isostatic topologies, used for under-actuation, and one primary hyperstatic topology, used for enhanced stiffness and static characteristics. A robot or a configuration with a *hyperstatic topology* is one that is statically and kinematically indeterminate, or in other words, it is redundantly rigid, whereas an *isostatic topology* is one that is both statically and kinematically determinate, or in other words, it is minimally rigid. *Static redundancy* occurs when a mechanism or a structure becomes hyperstatic. The degree of static redundancy in the hyperstatic state is equal to the number of locked DOFs associated with the passive joints that would have to be unlocked to turn the system into an isostatic one. The degree of static redundancy in the hyperstatic state, r, can be expressed as

$$r = \left(N_j^A + N_j^{PL}\right) - d \tag{1}$$

where N_j^{PL} and N_j^A are the total number of lockable passive and actuated joints, respectively; d is the system order, with a value of three in $\mathbb{R}^2$, and six in $\mathbb{R}^3$. Eq. (1) is expressed with the underlying assumption that the actuation or locking action is applied to one non-redundant DOF of the joint, regardless of the number of DOFs of the joint itself. The degree of static redundancy can vary depending on the application. However, it is always equal to or greater than one in the hyperstatic state. It should be noted that Eq. (1) is only