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Research paper

Structural synthesis of a class of kinematically redundant parallel manipulators based on modified G–K criterion and RDOF criterion

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ABSTRACT

Based on the modified Grübler–Kutzbach (G–K) criterion and relative degrees of freedom (RDOF) criterion, a novel method is proposed for structural synthesis of a class of kinematically redundant parallel manipulators (KR-PMs) with spherical joints attached to a moving platform. First, a formula that can be used to calculate the number of kinematic joints not limited to basic joints is proposed, which is affected by the number of links including fixed base, links with multi-node, compound hinges, and the INTERNAL independent loops in parallel manipulators. Furthermore, the sum degrees of all the kinematic joints possesses a direct relationship with the number of kinematic joints, the number of spherical joints, and the type combination of spherical joints attached to the moving platform. Then, the relationship between the mobility M and the RDOF with intermediate variables is derived based on modified G-K criterion and RDOF criterion, which is the base of the proposed synthesis procedure. Next, the proposed synthesis procedure is performed with the synthesis conditions RDOF = 3 or 4, and some typical KR-PMs are obtained. Finally, the condition for proper selection of actuators for KR-PM is revealed. And the reasons for large configuration randomness of the synthesized KR-PMs are discussed.

1. Introduction

Parallel manipulator is a kind of mechanisms with closed loops, and typically consists of a moving platform that is connected to a fixed base by several kinematic limbs. Due to its potential applications and the claimed advantages over serial industrial robot, the parallel manipulator has attracted much attentions. Recent years, some scholars have tried to improve the performance of parallel manipulators by adding redundant actuators or redundant structures, and surely achieved significant results.

For parallel manipulator with redundant actuators, the mobility of the whole parallel manipulator is equal to the relative degrees of freedom (RDOF) of the moving platform, but less than the number of independent actuators. The scholar Merlet [1] pointed that the actuated redundancy can be used to increase reliability and get better load distribution in the actuators, and the prices to pay for such advantages are a higher complexity in design and some difficulties with the control. After

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Nomenclature

KR-PM	the kinematically redundant parallel manipulator
M	the mobility of the whole parallel manipulator, i.e. the number of independent actuators that needed to determine the unique configuration of the parallel manipulator.
RDOF	relative degrees of freedom
P	the prismatic joint
R	the revolute joint
P	the actuated prismatic joint
R	the actuated revolute joint
U	the universal joint
S	the spherical joint
d	the order of the parallel manipulator, and $d = 6 - \lambda$
λ	the number of common constraint
N	the number of spherical joints attached to the moving platform
n	the number of links including fixed base
g	the number of kinematic joints
f_k	the freedom of the kth kinematic joint
v	the number of redundant constraint after eliminating the common constraints
ξ	the passive degree of freedom
n_i	the number of spherical joint attached to the platform and determined by the i-system
i-system	The i-system is formed by the basic joint screws in generalized limb except the spherical joint attached to the moving platform
k_i	the rank of the i-system.
L_q	the number of links with q-node except the fixed base, $q \geq 3$
e_m	the number of compound hinges with m DOFs and constructed by $(m+1)$ links, $m \geq 3$
H	the number of INTERNAL independent loops, which does not contain the fixed base
$\$_i^r$	the structural constraint screw
$\$_i^{r,A}$	the actuated constraint screw
N[*]	the null space operation
M_{cl}	the mobility of the single closed loop linkage
n_{cl}	the number of links including fixed base in single closed loop linkage
g_{cl}	the number of kinematic joints in single closed loop linkage
v_{cl}	the number of redundant constraint in single closed loop linkage
n'	the number of surplus links except the fixed and moving platforms
g'	the number of surplus joints except the spherical joints attached to the moving platform
n_{req}	the required links to realize the combination types of spherical joints
g_{req}	the required joints to realize the combination types of spherical joints
F3	three independent constraint forces
C3	three independent constraint couples
$\$^r_{sub-\lim b}$	the constraint screw provided by sub-limb of closed-loop in kinematic limb
$\$^{r,T}_{sub-\lim b}$	the reciprocal transpose of the constraint screw $\$^r_{sub-\lim b}$
$\$^{equiv.}_{closed-loop}$	the equivalent screw motion of the closed-loop in kinematic limb

that, many researchers have studied on the parallel manipulator with redundant actuators, such as Kock [2], Gogu [3–5], Saglia [6], Kim [7], Xie and Liu [8,9], Qu [10], Wu [11,12] and so on. Since the redundant actuators are obtained by adding redundant limbs with active actuators, this often leads to over-constrained parallel mechanism [13]. The over-constrained condition makes a higher requirement on the manufacturing and assembly. However, the manufacturing tolerance and assembly tolerance cannot be eliminated, which cause the internal stresses in a assembled mechanism. When there exist uncoordinated inputs, the internal stresses will be enlarged, which will aggravate the energy consumption, even lead to mechanism damage.

In order to reduce the internal stresses in the assembled mechanism, some scholars have tried to design a kind of lower order over-constrained or non-over-constrained redundant parallel manipulators, which can realize the mechanical self-coordination between inputs and outputs. Such design requirements lead to kinematically redundant parallel manipulators (KR-PMs). For KR-PM, the mobility of the whole parallel manipulator often is larger than the RDOF of the moving platform, and equal to the number of independent actuators. Since the mobility is equal to the number of independent actuators, the mechanical self-coordination will be realized, and the internal stresses problem also can be overcome. Therefore, kinematic redundancy is considered as an effective way to improve the performance of parallel manipulators. Many scholars have tried