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Type synthesis of parallel mechanisms by utilizing sub-mechanisms and digital topological graphs

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ABSTRACT

A type synthesis of various parallel mechanisms by utilizing sub-mechanisms and digital topology graphs is studied. The conditions for type synthesis of the parallel mechanisms with the sub-mechanisms are determined. Based on the determined conditions, the digital topology graphs are derived from different associated linkages, and the digital topology graphs are transformed into revised digital topology graphs for type synthesis of the parallel mechanisms with redundant constraints. The sub-mechanisms are transformed into simple equivalent limbs and their equivalent relations are analyzed. Seventeen novel parallel mechanisms are synthesized by utilizing the derived digital topology graphs, the revised digital topology graphs and the sub-mechanisms or the combinations of sub-mechanisms. The synthesized parallel mechanisms are simplified by replacing the complex sub-mechanisms with their simple equivalent limbs. Finally, the degrees of freedoms of all the synthesized parallel mechanisms are calculated to verify the correctness and effectiveness of the proposed approach.

1. Introduction

Type synthesis of mechanisms is a well known method for creating novel mechanisms [1–6]. In this aspect, Gogu 2008 studied the type synthesis of parallel mechanisms (PMs) and presented morphological and evolutionary approaches [1], he 2009 studied the translational topologies of closed mechanisms with two and three degrees of freedom (DoFs) [2], and he 2010 studied the topology synthesis of closed mechanisms with the planar motion of moving platform [3]. Johnson derived some associated linkages for the planar mechanisms using a determining tree and synthesized many planar mechanisms by utilizing the associated linkage [4]. Huang et al. conducted the type synthesis of PMs by utilizing Lie group method and screw-theory [5]. Yang et al. studied the topology structure design of mechanisms [6]. The approach of topology graph has been widely applied to the type synthesis of closed mechanisms [2,3,6,7]. A contracted graph without any binary links is applied to derive the topology graph. In this aspect, Sohn, Vucina and Freudenstein [7,8] and Tsai et al. [9] proposed an approach of topology graph and a contracted graph and applied them to the type synthesis of the closed mechanisms. Yan and Kang [10] studied the configuration synthesis of mechanisms by changing types and/or motion orientations of some joints. Caro et al. [11] presented some synthesis rules to obtain a complete minimum set of serial topologies capable of producing Schönflies-motion motions. Pucheta et al. [12,13] synthesized the planar linkages based on the constrained sub-graph isomorphism detection and the existing mechanisms. Saxena and Ananthasuresh [14] selected the best configuration of some mechanisms based on kinetostatic design specifications. Tarcisio et al. [15] studied the topological synthesis of a PM based on the wrist design requirements. Some (i=3, 4, 5)-DoF PMs were synthesized by Kong and Gosselin by utilizing the

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Nomenclature

DoF	degree of freedom
PM	parallel mechanism
m	moving platform
B	fixed base
AL	associated linkage
TG	topology graph
DTG	digital topological graph
P, R	prismatic and revolute pairs
U, C, S	universal, cylinder, spherical pairs
J	connection joint with one-DoF
N	the numbers of links
n	the numbers of joints
n_s, n_u, n_c, n_p, n_r	the numbers of S, U, C, P, R
b, t, q	binary, ternary, quaternary links
p, h	pentagonal, hexagonal links
e_i	the ith edge
n_i (i=2, ..., 6)	the numbers of b, t, q, p, h
^sL_j	the sub-serial mechanism with j actuators
^kL_j	k-DoF planar closed mechanism with j actuator, k=0, 1, 2, 3
L_k	k-DoF PM with k actuator, k=3, 4, 5
v	the numbers of redundant constraints
ζ	passive DoF

screw theory and virtual chain approach [16–18]. Lu et al. derived some unified planar/spatial associated linkages, and several contracted graphs from associated linkage by utilizing topology matrices, they also derived topology graphs from the contracted graph by visual inspection [19]. In addition, Lu et al. discovered the relations between associated linkage, redundant constraint, and DoF of the PMs [20], they also derived valid kinematic limbs of 3-DoF PMs without redundant constraint [21] and derived complicated topology graph using array for the type synthesis of 3-, 4-DoF PMs [22]. The above mentioned studies have their merits and different focuses. Currently, the associated linkage, the topology graph, the contracted graph, arrays and screw theory are mainly used for the type synthesis of the kinematic chains and their structures [4,5,11,14,16–18], the closed planar mechanisms [4,9,12,13] and the PMs without redundant constraint [16–19,21].

When the serial mechanism, the closed planar mechanism and the k-DoF PM as $k < i$ are taken as the sub-mechanisms of the i-DoF PMs, the i-DoF PMs may possess the redundant constraints and have some merits, such as enlarged position and orientation workspace, increased the capability of load bearing and the high stiffness, simplified structure and control [13,23]. These merits may enable the PMs to satisfy more requirements in robots, machine tools, automobiles, airplanes, micro mechtronic manipulators, and to standardize the manufacturing and assembly of the sub-mechanisms. However, so far, the relative methods and rules have not been systematically studied for the type synthesis of the i-DoF PMs with the redundant constraints constructed by k-DoF sub-PMs, where $k < i$, by utilizing the digital topological graph (DTG) method. For this reason, this paper focuses on the type synthesis of the PMs by utilizing the sub-mechanisms and the DTGs. Following problems are solved: (1) construct various DTGs of the PMs from the associated linkages; (2) determine the relationships between the DTGs and the equivalent limbs of the sub-mechanisms; (3) synthesize the i-DoF PMs by utilizing the sub-mechanisms, the DTGs and the revised DTGs.

2. Sub-mechanisms and their merits

A sub-mechanism may be a sub-serial limb, or a sub-planar closed mechanism, or a k-DoF PM as $k < i$ or their combination. Let (R, P, U, S) be the (revolute, prismatic, universal, spherical) kinematic pairs, respectively. Let ^sL_j (j=0, 1, 2, 3) be the sub-serial limb with j actuators connected in series. Let ^kL_j (j=0, 1, 2; k=1, 2, 3) be the sub-planar closed mechanism with j actuators and k DoFs. Let L_k (k=3, ..., i-1) be a k-DoF sub-PM with k actuators as $k < i$. Each of them has several merits as follows.

When a SP-type or a UP-type sub-serial limb $^sL_0$ is taken as a passive constrained limb for connecting the moving platform with the base in the i-DoF PMs, a tiny self motion of the PMs can be removed effectively, and the rotational stiffness of the PMs can be increased [21,24]. When a SPS-type sub-serial limb $^sL_0$ is taken as an elastic auxiliary limb for connecting the moving platform with the base in the i-DoF PMs, the workload applied onto the moving platform of the PMs can be born by several SPS-type elastic auxiliary limbs $^sL_0$ and the required active force of the active limbs can be reduced largely.

When each of the sub-serial limbs ^sL_j (j=2, 3) is taken as a limb for connecting the moving platform with the base in the i-DoF PMs, the total number of the required limbs must be reduced. Thus, the interference between the limbs and the moving platform may be avoided easily, and the workspace of the i-DoF PMs can be enlarged. In addition, since other active limbs of the i-DoF PMs can be transformed into the SPU-type linear active limbs which are not sensitive to the manufacturing errors, not only the tiny self motion of the PMs can be removed effectively, but also their capability of load bearing can be increased.

When one of the planar closed mechanisms ^kL_j (j=0, 1, 2; k=1, 2, 3) is taken as a sub-planar limb for connecting the moving platform with the base in the i-DoF PMs, the sub-planar limb may have the following merits [20]:

1. The sub-planar closed mechanism only includes the revolute pair and prismatic pair. The revolute pair has a larger capability of pulling force bearing than that of the spherical pair.
2. The precision of the revolute pair is higher than that of the spherical pair under a large cyclic loading because the backlash of the revolute pair can be eliminated more easily than that of the spherical pair by adding a preload.
3. The workspace of the i-DoF PM can be increased because the rotation angle of the revolute pair is larger than the rotation cone angle of the spherical pair before interference.
4. The whole mechanism can be simplified because the number of the binary links is reduced.
5. It is easy to increase the mechanical advantage, such as to increase the displacement or the velocity of the moving platform, and to