

Preface

Robot mechanisms, especially parallel robot mechanisms, have raised great interest among many mechanism researchers during the last two decades. Compared with traditional serial mechanisms, parallel robot mechanisms offer many advantages, such as high accuracy, rigidity, load-to-weight ratio, etc. Early research of parallel robot mechanisms was focused mainly on the six-DOF Gough–Stewart platform. In the last decade, parallel mechanisms with fewer DOFs attracted the attention of researchers and gradually became popular in many fields.

There are two principal goals in researching mechanism topology: One is to provide systematic theories and methods, which eventually guide the topology design of robot mechanisms. The other is to establish new composition principles of mechanisms, based upon which a unified modeling of topology, kinematics, and dynamics of mechanisms can be achieved.

This book introduces the creative research achievements of the authors on mechanism topology over the past more than thirty years. The essential points can be concentrated as follows:

(1) **Three fundamental concepts**

(a) Geometrical Constraint Type of axes (see Chap. 2).

The subject concept describes the geometrical constraints among axes of kinematic pairs. The geometrical constraint type of axes, together with the kinematic pair type, and the connection relations among links are three basic elements of topological structures. It should be emphasized that the symbolic expression of a topological structure constructed in this manner is independent of the motion positions of a parallel mechanism (excluding singular positions).

(b) POC Set (see Chap. 3)

The POC set, derived from the unit vector set of the velocity of a link, the POC set describes the position and orientation characteristics of the relative motions between any two links of a mechanism. It depends only on the topological structure of the mechanism and is independent of the motion positions of the mechanism (excluding singular positions).

(c) SOC Unit (see Chap. 2)

The SOC unit is used as the basic structure unit to develop four basic equations of mechanism topology (see Chaps. 4–6).

(2) **Mechanism composition principle based on SOC units**

The mechanism composition principle based on SOC units is proposed to establish the systematic theory for unified modeling of topology, kinematics, and dynamics of mechanisms (see Chap. 7).

(3) **Four basic equations**

The equations listed in the following Paragraphs (a) through (c) reveal the mapping relationship among the topological structure, the DOF and the POC set of a mechanism. The equation addressed in the following Paragraph (d) provides the theoretical cornerstone for building up a systematic theory and method for topology, kinematics, and dynamics of mechanisms based on the SOC-unit modeling.

(a) POC Equation of Serial Mechanisms (see Chap. 4)

This equation is used for topological structure analysis and synthesis of serial mechanisms. Eight linear symbolic operation rules and two nonlinear criteria are created to support this equation.

(b) POC Equation of Parallel Mechanisms (see Chap. 5)

This equation is used for topological structure analysis and topology design of parallel mechanisms. Twelve linear symbolic operation rules and two nonlinear criteria are provided for this equation.

(c) The General DOF Formula (see Chap. 6)

This is the formula to calculate the DOF of parallel mechanisms and multi-loop spatial mechanisms.

(d) The Coupling Degree Formula for AKC (see Chap. 7)

This is the formula to calculate the coupling degree of the Assur kinematic chain (AKC). The coupling degree represents the complexity of kinematic and dynamic analyses of the AKC.

The above four equations (formulas) depend only on the topological structures of a mechanism and are independent of motion positions of the mechanism (excluding singular positions). It is not necessary to establish a fixed coordinate system when using these four equations.

(4) **One systematic method for topology design of parallel mechanisms** (see Chaps. 8–10)

Based on the three fundamental concepts, the mechanism composition principle based on SOC units, and the four basic equations mentioned in Paragraphs (1), (2), and (3). The systematic topology design of parallel mechanisms, developed from the essential points (1), (2), and (3) mentioned above, possesses the following characteristics:

- (a) The design has two stages: Stage 1 synthesizes structures obtaining many kinds of parallel mechanisms; Stage 2 analyzes the performances, classifies types, and subsequently optimizes the parallel mechanisms synthesized from Stage 1.

- (b) The design operation is independent of the motion positions of a mechanism (excluding singular positions) and the fixed coordinate system (i.e. it is not necessary to establish the fixed coordinate system); therefore it is a geometrical method. This ensures a full-cycle DOF of the parallel mechanism and the generality of geometric conditions of assembling branches between the two platforms.
- (c) Each individual design step follows an explicit formula or the guidelines of design criteria, making the operation simple and feasible.

It may be beneficial to outline the following chronological milestones of our researches.

- A. 1983–1986:** A general method for structural synthesis of overconstrained spatial single-loop mechanisms was provided, based on which new structure types were synthesized (Ref. [2] in Chap. 1, and Ref. [9] in Chap. 2). The geometrical constraint type of axes (the type of geometrical constraint on axes of adjacent kinematic pairs, which was originally called the dimensional constraint type) was introduced as the third key element to describe the topological structure of a mechanism. The other two key elements are: the kinematic pair and the connection relation between links. The mapping relationship between the number of independent displacement equations and the topological structure of overconstrained spatial single-loop mechanisms was revealed based on these three key elements.
- B. 1985–1996:** The composition principle based on the SOC units for planar mechanisms was proposed. An SOC-based structure synthesis method for planar mechanisms was presented, and the corresponding structural types were obtained (Ref. [59] in Chap. 1). The key points are as follows: (a) the SOC-based structure unit, (b) the constraint degree formula for a planar SOC, and (c) the coupling degree formula for the planar AKC. These three points were later used to form the systematic theory and method for unified modeling of topology, kinematics, and dynamics of planar mechanisms (Ref. [59, 61, 62, 65, 69] in Chap. 1). This theory and method was described in detail in the first author's monograph, which was written in Chinese, "Basic Theory of Planar Mechanisms: Structure, Kinematics and Dynamics," China machine press, Beijing, 1996 (Ref. [61] in Chap. 1). It is well-known and frequently cited by Chinese scholars.
- C. 1995–2005:** An SOC-based structure synthesis method for parallel mechanisms was given, and structural types with $\text{DOF}=2-6$ were derived (Ref. [3, 27, 28–30, 31, 32, 33–37] in Chap. 1). The innovations of this phase are as follows:
 - (1) It was discovered that the topological structures constructed by the three basic elements mentioned in the Milestone (A) is motion process invariant (excluding singular positions).
 - (2) The POC set, originally named "POC Matrix" and derived from the unitary vector set of the link velocity, depicts the relative movement characteristics of any two links. It is independent of the motion positions (excluding singular positions) and the fixed coordinate system.

- (3) The POC equation for a serial mechanism and its operation rules are independent of the motion positions and the fixed coordinate system.
- (4) The POC equation for a parallel mechanism and its operation rules are independent of the motion positions and the fixed coordinate system.

Published in 2004, our Chinese renowned treatise, “Theory of Topological Structure for Robot Mechanisms” China machine press, Beijing (Ref. [32] in Chap. 1), describes the systematic theory and application of the structural synthesis of parallel mechanisms. This is the first academic book in the world on structural synthesis of parallel mechanisms.

D. 2006–2016: The innovations during this period are as follows:

- (1) A general DOF formula for parallel mechanisms and arbitrary spatial multi-loop mechanisms was gradually established (Refs. [40–42] in Chap. 1). The creative points are: (a) a full-cycle DOF obtained, (b) a criterion to determine inactive kinematic pairs, (c) a criterion to determine driving pairs, and (d) a simplified method, based on the topological equivalent principle, to calculate the DOF of a mechanism.
- (2) Using this general DOF formula for spatial mechanisms, the composition principle based on SOC units was able to be extended to general spatial mechanisms. The constraint degree formula for a spatial SOC and the coupling degree formula for the spatial AKC are presented (Ref. [43] in Chap. 1).
- (3) A general method for topology design of PMs is proposed. The design process includes two stages: (a) Structure synthesis. Many structure types are obtained. (b) Performance analysis, classification and optimization of PM structure types (refer to Chaps. 9–10).
- (4) It provides a theoretical basis for establishment of a unified SOC-based method for structure synthesis and kinematic (dynamic) analysis of general spatial mechanisms (Ref. [43] in Chap. 1).

E. 2013: The paper “On the Correctness and Strictness of the POC Equation for Topological Structure Design of Robot Mechanisms” was published in JMR (Ref. [39, 38] in Chap. 1) to answer the questions or doubts of some researchers on our theory: (a) Is this theory correct or rigorous? and (b) Can this theory be used to solve any topology design problems which cannot be solved by other existing methods?

In conclusion, the five milestones summarized above are foundations of the systematic theory and methodology demonstrated in this book.

Provided below is a brief of the idea of my research on the theory mentioned above.

In 1959, when I was a junior at Qinghua University (Beijing) studying the course “Theory of Machines,” I had quite a few doubts about the DOF formula for spatial mechanisms. Meanwhile, I was deeply interested in the Assur structure theory. In this respect, my long-term research on the subject originated from the doubts and curiosity of mine at that time. However, I was not able to concentrate my research on the subject until the Ten-year Catastrophe (1966–1976) which is also known as

the Cultural Revolution was over. If my research is officially counted from my presenting the first research paper on the subject at the sixth IFToMM world congress on the theory of machines and mechanisms held in New Deli in 1983, it has been thirty-five years—never a short term in anyone’s life!

Introduction of the three new concepts based on non-logical thinking enables the theory to clearly depict its physical significance, and the four basic formulas derived from logical reasoning give the theory a precise mathematical structure. As a result, the theory well demonstrates the beauty of simplicity—a perfect reflection of the Daoist philosophy “Greatest truths are always the simplest.”

As the beauty of simplicity in theories, the trueness of emotion, and the rich colorfulness of the Mother Nature are closely linked, appreciation and understanding of and resonance to such beauties further stimulate new instinct and inspiration.

In addition, adoration of the spirit of independence and freedom of thought, extensive reading with reflection, emotion and sense in making friends, and thinking of the light or darkness in the social development enable people to have a broader vision and promote in-depth thinking. The passion and aesthetic feeling generated from life have become a pillar of spirit in my long-lasting concentrated academic study.

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