Preface

2nd Edition

This second edition of *Geometric Design of Linkages* revises and updates our formulation of the kinematic theory of linkages. Four new chapters have been added that present the analysis and synthesis of multiloop planar and spherical linkages, and the synthesis theory for spatial serial chains.

An introduction to linkage graphs and linkage enumeration has been added to Chapter 1 to provide background for the new chapters on the synthesis of multiloop linkages, and the use of the Dixon determinant to analyze planar multiloop linkages has been added to Chapter two.

Chapters three, four, and five are the same as before with corrections of minor errors. Chapter six is new and presents a methodology for the synthesis of planar six-bar and eight-bar linkages by constraining three-degree-of-freedom 3R open chains or 6R closed chains, respectively. Examples are provided that demonstrate the technique.

Chapter seven is the same as Chapter six in the previous edition but now includes a section on the analysis of multiloop spherical linkages. Chapters eight and nine are the same as Chapters seven and eight in the previous edition, again with corrections of minor errors,. The new Chapter 10 parallels the new Chapter six and presents a way to design spherical six-bar and eight-bar linkages by constraining 3R open and 6R closed spherical chains.

Chapters 11, 12, and 13 are the same as Chapters 9, 10, and 11 in the previous edition. Chapters 14 and 15 on the synthesis of spatial serial chains are new and were the result of research with Haijun Su and Alba Perez-Gracia. Chapter 14 formulates and solves using numerical homotopy the synthesis equations for five-degree-of-freedom serial chains that can position a wrist center on specific algebraic surfaces, termed reachable surfaces. Chapter 15 introduces the Clifford algebra of dual quaternions and its use in formulating the synthesis equations for general spatial serial chains. Chapter 16 is the same as Chapter 12 in the previous edition.

I continue to benefit from the contributions of teachers, colleagues, and students toward a geometric synthesis theory for linkage systems, recently from Jeff Ge, Mohan Bodduluri, John Dooley, Pierre Larochelle, Andrew Murray, Fangli Hao, Curtis Collins, Alba Perez-Gracia, Haijun Su, Nina Robson, Duanling Li, and my coauthor Gim Song Soh. In addition, I am grateful for the continued inspiration of Qizheng Liao and Bernard Roth.

Finally, I gratefully acknowledge the support of the Engineering Design Program of the National Science Foundation that has made this book possible.

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First Edition

This book is an introduction to the mathematical theory of design for articulated devices that rely on simple mechanical constraints to provide a complex workspace for a workpiece or end-effector. Devices ranging from windshield wipers to robot manipulators and mechanical hands are examples of these systems each of which has a skeleton of links connected by joints called a linkage. The function or task for the device is defined as a set of positions to be reached by the end-effector. The goal is to determine the dimensions of all of the devices that can achieve a specific task. Formulated in this way the design problem is purely geometric in character.

This text blends two approaches to this design problem in order to develop the intuition needed to move from planar to spatial linkage design. One approach considers the geometric configurations of points and lines generated as a moving body is displaced through a finite set of positions. This is the foundation for graphical methods for planar linkage synthesis and can be generalized to spherical and spatial linkage design. A separate approach focuses directly on solving the nonlinear constraint equations that characterize a mechanical connection. This provides convenient equations for planar and spherical linkage design, and is crucial to addressing the geometric challenge of spatial linkage design.

This unified formulation requires a range of mathematical tools. The basic language is vector algebra and matrix theory, which should be familiar to junior and senior university students. However, something among the techniques ranging from graphical constructions, spherical trigonometry, complex vectors, and quaternions to line geometry and dual vector algebra is certain to be unfamiliar. For this reason, the presentation is designed to introduce these techniques, and additional background is provided in appendices.

The first chapter presents an overview of the articulated systems that we will be considering in this book. The generic mobility of a linkage is defined, and we separate them into the primary classes of planar, spherical, and spatial chains.

The second chapter presents the analysis of planar chains and details their movement and classification. Chapter three develops the graphical design theory for planar linkages and introduces many of the geometric principles that appear in the remainder of the book. In particular, geometric derivations of the pole triangle and the center-point theorem anticipate analytical results for the spherical and spatial cases.

Chapter four presents the theory of planar displacements, and Chapter five presents the algebraic design theory. The bilinear structure of the design equations provides a solution strategy that emphasizes the geometry underlying linear algebra. The five-position solution includes an elimination step that is probably new to most students, though it is understood and well received in the classroom.

Chapters six and seven introduce the properties of spherical linkages and detail the geometric theory of spatial rotations (now Chapters seven and eight, 2nd edition). Chapter eight presents the design theory for these linkages (now Chapter nine), which is analogous to the planar theory. This material exercises the student's use of vector methods to represent geometry in three dimensions. Perpendicular bisectors in the planar design theory become perpendicular bisecting planes that intersect to define axes. The analogue provides students with a geometric perspective of the linear equations that they are solving.

Chapter nine introduces the analysis of spatial linkages including open chains that are closely related to robot manipulators (now Chapter 11). The complexity of spatial linkages requires the introduction of new techniques. However, we maintain a point of view that emphasizes the similarity to the planar and spherical theories. For example, the constraint equations of planar and spherical linkages are shown to be special cases of those for spatial linkages.

Chapter 10 develops the geometry of spatial displacements (now Chapter 12). Here, we find that the screw triangle and the center-axis theorem must be formulated using lines rather than points. Dual vector algebra is introduced to provide vector operations for calculations with the Plücker coordinates of lines. The result is that geometric calculations with line coordinates are identical to the more familiar vector calculations with point coordinates.

Chapter 11 presents the design theory for spatial chains, and Chapter 12 introduces the geometry of linear combinations of lines that arise in the construction of spatial linkage systems (now Chapters 13 and 16). While the design techniques for planar linkages are well developed, there is room for much more work in the design and use of spatial linkages.

I am pleased to express my gratitude for the contribution of many teachers and colleagues whose work over the years has developed and clarified linkage design theory. This book includes results of the insight, commitment, and hard work by Jeff Ge, Mohan Bodduluri, John Dooley, Pierre Larochelle, Andrew Murray, Fangli Hao, Curtis Collins, Alan Ruth, Shawn Ahlers, and Alba Perez. I have also benefitted from the insight of Qizheng Liao and the inspiration of Bernard Roth. Finally, the support by the Division of Design, Manufacturing, and Industrial Innovation of the National Science Foundation that has made this book possible is gratefully acknowledged.

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