



Research paper

A novel geometric approach for planar motion generation based on similarity transformation of pole maps

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ABSTRACT

Burmester theory provide guidance solutions by dyad precise synthesis with up to five given exact poses. But it has little influence on solution mechanism features and not suitable for the rigid body guidance mechanisms without “center- and circle-point” structure or planar motion generation with partly fuzzy positions. This paper proposed a geometric synthesis approach, which is composed of fuzzy position construction, function module selection, fuzzy pole determination and quasi-similarity transformation. Based on quasi-similarity transformation theory, pole maps were built up as unified geometric identification between given positions and guidance mechanisms. Various normalized mechanism function modules were established with full topology information, including dimension ratios. As a bridge, the mapping rules directly revealed the relationship between guidance tasks and guidance mechanisms. Finally, this feature-driven geometric synthesis approach was demonstrated with two examples, a belt mechanism for exact three-position task and a geared linkage mechanism for fuzzy four-position task.

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1. Introduction

The body guidance problem for specified plane positions, also known as the planar motion generation, is one of the basic tasks in mechanism design theory. Ever since the development of modern kinematics, researchers have been working on systematic means to solve the structure synthesis and dimension synthesis problems of this task [1]. Despite a great number of synthesis methods has been developed, such as graphical methods [2–4], analytical methods [5–7], and atlas methods [8–10], many problems still remain unsolved. The earliest approach to the finite planar motion generation was proposed by Burmester [11], who pointed out that a planar four-bar mechanism has the ability to guide a rigid body through up to five finitely separated positions accurately. However, the classical synthesis techniques based on Burmester theory are limited to the four-bar mechanism as the simplest mechanism structure, and the solutions composed of revolute joints or RR dyads may occur unexpected defects [12,13], such as Grashof's defect, order defect, circuit defect and branch defect. Since these synthesis methods only deal with one dyad each time based on the “center- and circle-point” structure, the numerically feasible solution need to be examined whether there exists functional defects. Thus, the solution mechanism needs to be optimized by changing the fixed or moving pivots in order to meet expected functional requirements.

Considering the demand of simple and practical synthesis methods for planar motion generation in engineering practice, Lohse [14] investigated the poles that associated with all desired positions and the determination of a fixed pivot by

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intersection of pole curves. Then, Tong and Chiang [15], Lin and Chiang [16] applied the pole method based on the half of the rotation angle of the body in spherical case for path generators and function generators respectively, but this method still need to find the center- and circle-point curve. Zimmerman [17,18] proposed a graphical four-bar mechanism synthesis method for rigid-body guidance and coupler point guidance, using the poles and rotation angles as constraints to define guidance links, which is faster and simpler than traditional graphical synthesis methods, but this method is based on the circle-center point pairs. For the planar approximate motion generation problems, the methods based on kinematic mapping presented by De Sa [19] have been widely used. Hayes et al. [20] applied kinematic mapping to approximate type and dimension synthesis of planar four-bar mechanisms for rigid body guidance. Zhao et al. [21] proposed a synthesis approach to N-pose motion approximation problem using algebraic fitting method that based on kinematic mapping, and Ge et al. [22] extend this task driven approach to unified type and dimensional synthesis of planar four-bar mechanisms, using algebraic fitting of a pencil of G-manifolds. Kalnas and Kota [23] presented a method in which intermediate positions are described as distributions, with Monte Carlo simulation used in probabilistic mechanism analysis and synthesis, which can expand the resulting set of acceptable solutions. Although these researches have made great contributions to the development of kinematic synthesis, and have increased the influence on function properties to a certain extent during synthesis, the defects caused by the fundamental theory still exist.

In order to overcome the limitation of linkage mechanism and the uncertainty of solution mechanism features by Burmester theory, we solves the planar motion generation problem by separating the mechanism features into kinematic characteristics and guidance function in previous work [24–28], this paper will further extend the geometric approach for fuzzy motion generation tasks, which effectively guarantee the solution mechanism to possess expected features through position deviation within a given tolerance range. The main contributions of this work are (1) various mechanism function modules were established for synthesis under no limitation of four-bar mechanism (2) the mapping rules directly connected guidance tasks with function modules to simply the complicated synthesis into dimension type and initial position determination (3) devising a feature-driven geometric synthesis approach by fuzzy position construction and quasi-similarity transformation for the fuzzy motion generation tasks.

The rest of this paper is organized as follows. In Section 2, the synthesis methodology based on geometrical similarity transformation of pole maps is briefly presented. In Section 3, the function modules of various normalized mechanisms are established. In Section 4, the mapping rules between guidance tasks and guidance mechanisms are revealed. In Section 5, based on the construction of solution space for fuzzy positions and the predetermination of function modules with fuzzy poles, the fuzzy motion generation task is solved by quasi-similarity transformation of pole maps. In Section 6, two numerical examples for the exact three-position synthesis and the fuzzy four-position synthesis are given to illustrate the validity of proposed methodology.

2. Synthesis methodology based on similarity transformation

2.1. Position description by the pole map

According to the kinematic geometry [29], the relative displacement of two plane positions $E_j(U_j, \beta_j)$ and $E_k(U_k, \beta_k)$ can reach each other through a single rotation β_{jk} about the pole P_{jk} , which is determined by complex number as [30]

$$P_{jk} = \frac{i}{2} \frac{U_k e^{-i\alpha_{jk}} - U_j e^{i\alpha_{jk}}}{\sin \alpha_{jk}} \quad (1)$$

where

$$U_j = x_{U_j} + iy_{U_j}; U_k = x_{U_k} + iy_{U_k}; \alpha_{jk} = \frac{1}{2} \beta_{jk} = \frac{1}{2} (\beta_k - \beta_j) \quad (2)$$

Then, n prescribed guidance positions can be described by $n - 1$ poles $P_{1i} (i = 2, \dots, n)$ that relative to the initial position E_1 , which form a pole map Γ_P in the reference plane E_0 .

Similarly, the displacement of two coupler motion positions $R_j(A_j, \vartheta_j)$ and $R_k(A_k, \vartheta_k)$ of a guidance mechanism can be described by a single rotation ϑ_{jk} about the pole Q_{jk} , and the coordinates of Q_{jk} are expressed as [30]

$$x_{Q_{jk}} = \frac{x_{A_j} + x_{A_k}}{2} + \frac{y_{A_j} - y_{A_k}}{2 \tan \gamma_{jk}} \quad (3a)$$

$$y_{Q_{jk}} = \frac{y_{A_j} + y_{A_k}}{2} - \frac{x_{A_j} - x_{A_k}}{2 \tan \gamma_{jk}} \quad (3b)$$

where

$$\gamma_{jk} = \frac{1}{2} \vartheta_{jk} = \frac{1}{2} (\vartheta_k - \vartheta_j) \quad (4)$$

Consequently, n coupler positions that relative to R_1 can be described by a succession of poles $Q_{1i} (i = 2, \dots, n)$, which form a pole map Γ_Q in the fixed frame coordinate system.

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