Mechanism and Machine Theory 104 (2016) 130–160

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmt

Topology optimization of planar linkage systems involving general joint types

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ARTICLE INFO

Article history:
Received 24 November 2015
Received in revised form 20 May 2016
Accepted 22 May 2016
Available online 9 June 2016

Keywords:
Spring-connected block model
Planar linkage mechanism
Automatic mechanism synthesis
Topology optimization
General joint types

ABSTRACT

The simultaneous synthesis of the number and dimension of planar linkage mechanisms has opened a new possibility in mechanism synthesis. Mechanisms with revolute joints were a main concern so far but planar mechanisms with general joints including prismatic joints cannot be synthesized. This study aims to overcome the current difficult by proposing a new synthesis method. The key idea in the proposed approach is to parameterize joint types directly, unlike earlier methods parameterizing ground link skeletons connected by revolute joints. So, we propose a new concept of “double-springs” that can be used to connect a finite number of ground rectangular rigid blocks that discretize a given synthesis domain. Rigid blocks are elaborately connected by two sets of one-dimensional springs, i.e., double-springs and their stiffness values are varied by design variables. The connectivity of the double-springs dictated by the stiffness values determines the synthesized link mechanisms. We explain why it is crucial to use the double-spring concept for the synthesis of general joints such as prismatic joints. Various benchmark problems were considered to demonstrate the validity of the proposed method.

1. Introduction

It is important to synthesize linkage systems that have intended functions. From this necessity, there have been many research related to mechanism synthesis. The investigations mainly focused on type, number or dimensional syntheses [1–11]. However, there is little effort on the simultaneous number and dimensional syntheses. An attempt for the simultaneous synthesis using a genetic algorithm was reported [12] but the synthesis of an arbitrary topology with dimensional synthesis was not performed. Thus, topology optimizations of linkage systems, which simultaneously determine the number and dimension of a desired linkage mechanism, have been previously studied [13–25]. Among them, gradient-based methodologies [13,15,16,18–20,22,24,25] are promising because of their computational efficiency. In an attempt to find a globally optimal solution, one could consider using stochastic methods. But in this study, they are excluded because a typically large number of design variables (more than 200) is needed for the simultaneous number and dimensional synthesis and highly nonlinear kinematic analysis is involved. Although there were earlier studies [7,9] on the synthesis of linkage mechanisms involving prismatic joints, there is no study using gradient-based topology optimization methods concerned with such joints. Accordingly, we will review the technical aspect of the gradient-based topology optimization of linkage systems. Because mechanisms with various joint types including prismatic joints are used in industry (see, e.g., [26]), there is a need to develop a methodology that is capable to synthesize linkage

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http://dx.doi.org/10.1016/j.mechmachtheory.2016.05.015
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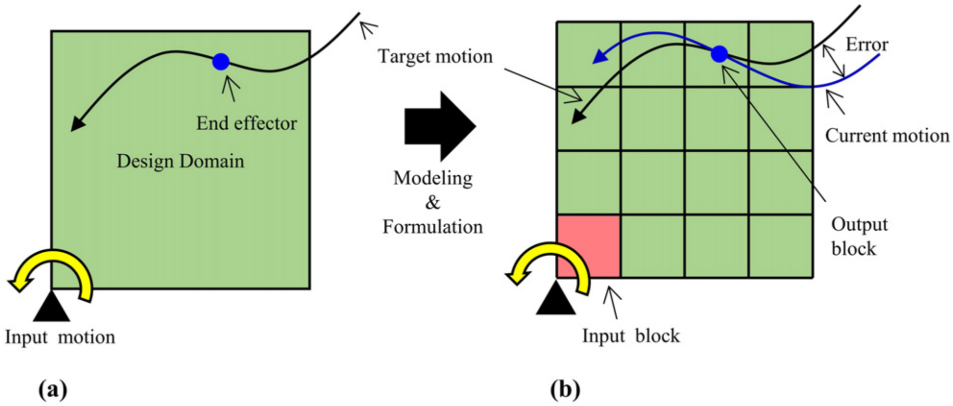

Fig. 1. (a) Problem description of the topology optimization-based synthesis of a planar mechanism for a given input and output motion in a specified design domain (b) discretization of the design domain by a number of rigid rectangular blocks connected by double-springs (springs are not shown).

mechanisms having various joint types. Motivated by this need, we aim to develop a new gradient-based topology optimization of planar linkage systems having not only revolute joints but also other joints including prismatic joints.

Fig. 1(a) shows a schematic illustration of the problem definition for topology optimization of linkage mechanisms. For a desired relation between target output motion and input motion as a function of time, we aim to synthesize a linkage mechanism that generates the target motion in the design domain. Here, no initial candidate mechanism information is assumed to be given. So, the synthesis method should be able to perform not only number but also dimensional syntheses simultaneously. To achieve this objective, a method based on the topology optimization can be considered. In earlier gradient-based topology optimization approaches for linkage synthesis, the design domain is typically discretized by bar [13,15,16,20,24], beam [25] or spring-connected rigid block elements [18,22]. In the present investigation, our model is based on a model using spring-connected rigid blocks in which spring stiffness values varied as functions of design variables govern block connectivity and determine layout mechanisms as shown in Fig. 1(b). The stiffness values are continuously changed during optimization iterations. When the optimization is converged, the stiffness values should reach their maximum or minimum bound values, from which specific links or specific joints can be identified (see [18,22] for more details). Because the existing models cannot deal with prismatic joints, a new model must be devised to be able to synthesis mechanisms having general joints. Besides, a linkage mechanism represented by the converged system should have the correct degree of freedom (DOF), i.e., 1 DOF. Because continuous design variables are used in the topology optimization-based mechanism synthesis for numerical efficiency, it is not trivial to satisfy the correct DOF exactly. The review of earlier studies suggests that there are two main issues in gradient-based optimization approaches for mechanism synthesis: a modeling issue and a formulation issue (ensuring the correct DOF). The modeling issue is concerned with how to represent various joint types, and the formulation issue, how to ensure the correct DOF of synthesized mechanisms.

Among the two issues, we will be focused on the modeling issue in this study because mechanisms with general joint types cannot be synthesized without a proper model allowing the formation of general joints during optimization iterations. Then we will discuss the formulation issue. In the literature, there are two kinds of models available so far: one model using spring-connected rigid block elements [18,22] by which the existences of connecting joints are determined during the optimization and the other model using nonlinear elastic bar elements [13,15,16,20,24] or elastic beam elements [25] by which the existences of links are determined. When these models are used for gradient-based optimization, they must satisfy several requirements; linkages with various topologies should be synthesizable through these models, and analysis has to be stable for intermediate configurations associated with intermediate design variables that appear during optimization. Besides, the models should allow the determination of not only positions and types of joints between links but also the positions and types of ground joints connecting links and the ground. As we shall review below existing modeling techniques in some details, there is no technique or model allowing the synthesis of general joint types including prismatic joints.

Kawamoto and his colleagues [13,15,16] used nonlinear bar elements to discretize the design domain and assumed that they are connected by revolute joints. By gradient-based topology optimization, the existence of the nonlinear bar elements controlled by design variables is determined to synthesize a mechanism. Synthesis examples included simple inverter mechanisms, converter mechanisms, and short path generating mechanisms. In these studies, the only possible joint type was the revolute joint and the ground pivots were fixed during synthesis. Recently, Kim and Kim [24] have extended the nonlinear bar model by introducing zero-length springs to be able to represent ground revolute joints that connect link nodes and the ground. Ohsaki et al. [25] synthesized spatial converter mechanisms but no prismatic joint was considered.

Because the above-mentioned synthesis methods only control the existence of link elements, but not existence of joints, it is not possible to synthesize mechanisms consisting of various joints (revolute, prismatic and other joints) at different locations. To overcome this limitation, a new approach that simultaneously determines both the link layout and the link joint type should be developed. In search of such an approach, it was found that an alternative synthesis method by Kim et al. [18] could be extended towards this direction. Kim et al. [18] proposed the SBM (Spring-connected rigid Block Model) approach in which the design