Mechanism and Machine Theory 85 (2015) 189–204

Contents lists available at ScienceDirect

Mechanism and Machine Theory

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

Efficient constrained synthesis of path generating four-bar mechanisms based on the heuristic optimization algorithms

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ARTICLE INFO

Article history:
Received 19 June 2014
Received in revised form 8 November 2014
Accepted 24 November 2014
Available online 9 December 2014

Keywords:
Optimization
ICA
Parallel SA
Coupler point
Dimensional synthesis
Four-bar mechanism

ABSTRACT

This paper presents a comparative study of the dimensional synthesis of the path generating four-bar mechanisms using some heuristic optimization techniques. For this purpose, we implement the imperialist competitive algorithm (ICA) as a newly developed powerful optimization tool. The objective of the optimization algorithm is to minimize the tracking error of the mechanism coupler point. It is then modified to include the desired workspace limits. Furthermore, the paper presents an innovative method of imposing Grashof's law for generation of acceptable initial population to improve the optimization performance. In addition to the ICA, the paper implements the parallel simulated annealing approach for the cases of without and with prescribed timing. The results of our work will be finally compared to other heuristic algorithms such as GA, PSO and DE to provide a clear representation of the performance of each approach.

1. Introduction

In the mechanisms design context, the four-bar mechanism is considered as one of the fundamental linkages which is commonly used for performing various required tasks. A four-bar mechanism is designed to generate a prescribed task such as function, motion, or path [1]. A function generator is defined to correlate an input motion with an output motion. In the motion generator, the motion of the mechanism coupler link is controlled to follow some prescribed sequential positions. A path generator controls a point of mechanism coupler link in the plane such that it follows some prescribed path. The design process of a mechanism with unknown link lengths to reach this goal is commonly referred to dimensional synthesis. This important task can be handled by either quantitative or qualitative approaches.

In the quantitative approach, the analytical equations of the dimensional synthesis problem can be generated for obtaining unknowns. Although this approach leads to the exact solution of the synthesis problem, it is strongly limited by the number of precision points. However, in most real design problems synthesizing a four-bar mechanism includes many more analytical equations than unknown variables to describe the system's behavior. Consequently, one cannot simply solve the equations to get a solution. To remedy this undesired situation, the qualitative approach is utilized as an alternative. Based on this approach, in the absence of a well-defined algorithm, potential solutions are created to configure or predict the final solution. Based on this, a set of poses of the coupler point that best approximate a large number of prescribed positions is produced. This will guide us to the treatment of the dimensional synthesis problem by usage of an optimization algorithm. This approach takes precision points as input and finds optimal link lengths as design variables in an iterative procedure.

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http://dx.doi.org/10.1016/j.mechmachtheory.2014.11.021
0094-114X/

In recent few years, many researchers have focused on development and application of optimization algorithms to improve the four-bar mechanism performance. These algorithms are usually categorized within either analytical or numerical methods which the latter is further classified as deterministic methods or heuristic methods [2]. Deterministic methods are in general computationally faster than heuristic methods, although they can converge to a local minima or maxima, instead of the global one. On the other hand, heuristic algorithms can ideally converge to a global maxima or minima, although they are computationally slower than the deterministic ones. Heuristic approaches have been found to be more flexible and efficient than deterministic approaches especially for problems with relatively high number of design variables. In the literature devoted to this subject, most of these publications deal specifically with one of the above mentioned general purposes.

To establish a clear background with a specific research direction, we review here only those studies which deal directly with the optimal synthesis of path generating four-bar mechanism based on the heuristic methods. As one of the earliest works in this context, Zhou et al. [3] utilized a modified genetic algorithm (GA) and optimized the adjustable four-bar linkage. The optimal synthesis of the driven link for reducing structural error was performed to effectively reflect the overall difference between the desired and the generated paths. Optimal synthesis of planar four-bar mechanism was also followed in [4], in which a searching procedure was defined based on genetic and evolutionary algorithms. The main advantages of their work were its simplicity of implementation and its fast convergence to optimal solution, with no need of deep knowledge of the search space. The work presented in [5] combined genetic algorithm and fuzzy logic method to solve the problem of path generation in mechanism synthesis. The proposed method is made of a classical genetic algorithm coupled with a fuzzy logic controller (GA–FL). The work of Cabrera et al. [6] deals with solution methods to multiobjective constrained optimization of planar mechanisms using a new evolutionary algorithm. A searching procedure was developed, which applies genetic algorithms based on evolutionary techniques. Smaili and Diab [7] studied optimum synthesis of hybrid-task mechanisms using ant-gradient search method which is a combination of ant colony optimization and gradient search methods. For this purpose, they introduced the idea of hybrid task mechanisms. In [8] an alternative method of linkage synthesis using the simulated annealing (SA) approach was presented. Based on this technique, one can define n desired path points to be followed by a four-bar linkage. The synthesis problem was transformed into an optimization problem in order to use the simulated annealing algorithm. The dimensional synthesis method for a path generating four-bar mechanism having revolute joints with clearance was presented in [9]. Joint clearances were considered as virtual massless links. The proposed method used a neural network to define the characteristics of joints with clearance with respect to the position of the input link. The optimization of link parameters using the genetic algorithm with an appropriate objective function based on path and transmission angle errors was implemented. The work of Starosta [10] concerned synthesis of a path-generating four-bar linkage using the genetic algorithm and Fourier coefficients. To achieve this goal, he used Fourier coefficients of the curvature to represent a closed curve and applied genetic algorithm to optimize the linkage lengths. The synthesis of a four-bar linkage in which the coupler point performs approximately rectilinear motion was studied in [11]. For this purpose, they used the method of variable controlled deviations based on the differential evolution (DE) algorithm. Nariman-Zadeh et al. [12] used the hybrid multi-objective genetic algorithms for Pareto optimum synthesis of four-bar linkages considering the minimization of two objective functions simultaneously. The tracking error and transmission angle's deviation from 90° were considered as conflicting objective functions. In [13], Acharyya and Mandal studied three evolutionary algorithms namely genetic algorithm, particle swarm optimization (PSO), and differential evolution performance for designing four-bar mechanism with given curve path. They observed that the differential evolution shows fast convergence to the optimal result and very low error of adjustment to target points. Optimal synthesis of mechanisms for path generation using Fourier descriptors and global search methods was presented in [14]. For this purpose, an effective objective function based on Fourier descriptors was considered to evaluate only the shape differences between two curves. This function was minimized using a stochastic global search method derived from simulated annealing and Powell's method.

Rai et al. [15] introduced a unified procedure for synthesis of planar linkages that may take the form of rigid body, partially compliant or fully compliant mechanisms. The synthesis task was posed as a constrained optimization problem and was solved by a hybrid, elite-preserving genetic algorithm. Lin [16] studied a real-coded evolutionary algorithm for application to path synthesis of a four-bar linkage. This new evolutionary algorithm was obtained by combining differential evolution with the real-valued genetic algorithm. Khorshidi et al. [17] proposed a novel approach to the multiobjective optimal design of path generating four-bar linkages. Three, conflicting criteria including tracking error, deviation of its transmission angle from 90° and its maximum angular velocity ratio were considered as objectives of the optimization problem. A hybrid Pareto genetic algorithm with a built-in adaptive local search was employed to accelerate the search in the highly multimodal solution space. This approach extends its exploration to an adaptively adjusted neighborhood of promising points. The work presented by Matekar et al. [18] introduced a new error function for optimum synthesis of path generating mechanisms. Based on the proposed error function, an optimized path which matches closely with the prescribed poses can effectively be obtained. They used the method of differential evolution to carry out the optimization. Chanekar and Ghosal [19] investigated an optimization method for synthesis of adjustable planar four-bar, crank-rocker mechanisms. A two-stage method was used first to determine the parameters of the possible driving dyads in tracing multiple different and desired paths. Then, the remaining mechanism parameters were determined in a second stage where a circle-fitting procedure was used.

As it is obvious from the above literature review, many researchers have paid considerable attention to the subject of dimensional synthesis of four-bar mechanism using heuristic optimization algorithms. However, there is still a clear gap in implementing the imperialistic competitive algorithm (ICA) for synthesizing planar mechanisms. Therefore, our work presented here is first directed toward partially filling this gap in the literature. ICA is a newly developed powerful optimization tool which is based on the innovative evolutionary optimization method [20].

ICA has been used by researchers in different categories. These applications include, e.g.: image processing techniques [21], optimization of composite structures [22], data mining techniques [23], vehicle routing problem [24], flexible manufacturing problem [25],