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A novel differential search algorithm and applications for structure design

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ABSTRACT

Differential Search method is recently proposed to solve box constrained global optimization problems. In this paper, we will further extend this method to solve generalized constrained optimization problems, particularly for structure design optimization problems. To handle the constraints, we first propose a novel dynamic S-type soft-threshold penalty method. Then, the original constrained optimization problem is transformed into a sequence of unconstrained optimization problems. The proposed method is mainly comprised of two steps: parameter iteration and solution iteration. The parameter iteration is to update the dynamic penalty parameter through a soft-threshold scheme and the solution iteration is to implement Differential Search algorithm to solve an unconstrained optimization problem. Two benchmark sets, CEC2006 and CEC2010, and four engineering structure design optimization problems are solved by our proposed algorithm as well as many other swarm-based algorithms proposed in recent literatures. Numerical results show that our method can achieve better performance but with fewer function evaluations comparing with the existing algorithms.

1. Introduction

Many practical mechanical design problems can be cast as constrained optimization problems [1]. Unlike general nonlinear programming problems which only contain continuous or integer variables, mechanical design optimization problems usually involve both continuous and discrete variables. The continuous variables are used to represent standardization constraints such as the diameters of standard sized bolts, while the discrete variables are usually involved in the formulation of the design problem to select alternative options, such as gear teeth. Since discrete variables can be transformed into continuous variables through introducing equality constraints, we consider the following generalized optimization problem:

$$\begin{aligned} \min\ & y = f(x) \\ \text{s.t. } & g_j(x) \le 0, \ \text{for } j = 1, \dots, q, \\ & g_j(x) = 0, \ \text{for } j = q+1, \dots, m, \end{aligned}$$

where $x = (x_1, x_2, \dots, x_n) \in \mathbb{R}^n, l_i \le x_i \le u_i, i = 1, \dots, n,$ and the objective function $f(x)$ is continuous and defined on a search space, which is defined as an n-dimensional rectangle region (domains of variables defined by their lower and upper bounds).

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The feasible region set is defined by a set of m additional linear or nonlinear constraints $g_j(x)$. Let this problem be referred to as Problem (P).

To solve Problem (P), there are two main kinds of computational methods available: (i) mathematical programming methods that use approximation techniques to solve the optimization problem; and (ii) metaheuristic algorithms that mimic some natural phenomena including biology and evolution theory. Popular metaheuristic algorithms are swarm algorithms, including modified versions of Artificial Bee Colony (ABC) algorithm [2,3], Firefly Algorithm (FA) [4,5], Particle Swarm Optimization (PSO) [6–8], Social-Spider Optimization (SSO) algorithm [9], several variants of Differential Evolution (DE) algorithm [10–13], Backtracking Search Optimization Algorithm [14], Artificial Cooperative Search Algorithm [15] and some Evolutionary Strategy algorithms [16–19]. For general constrained optimization problems, mathematical programming methods are always stuck by the local minimizers. However, metaheuristic algorithms are able to escape from local minima [20]. Thus, how to introduce new efficient metaheuristic algorithms with higher potential and simpler usage is important.

To improve the performance of metaheuristic algorithms, many new techniques are introduced. In [21], a combination of Ant Colony Optimization with chaotic sequences are employed in continuous optimization problems of engineering design. PSO, Quantum-behaved PSO and Gaussian probability distribution are employed in continuous optimization problems of engineering design [22,23]. In [11,24,25], the hybrid DE to find global optimum in problems with complex design spaces and one hybrid algorithm enhances a basic DE with a local search operator, random walk with direction exploitation, to strengthen the exploitation ability, while the other adding a second metaheuristic, harmony search, to cooperate with DE algorithm so as to produce the desirable synergetic effect. A class of niche hybrid Cultural Algorithms for solving miscellaneous engineering optimization problems are studied in [26]. Although most algorithms mentioned above can be applied to structure design optimization problems, they are still computationally inefficient in some degree. In this paper, we will introduce a new modified Differential Search algorithm which can solve generalized constrained optimization problems and achieves better performances.

Differential Search (DS) algorithm is a new population-based metaheuristic optimization algorithm which is first introduced in [27] in 2012 to solve box constrained global optimization problems. Numerical experiments show that it achieves better performance than many other metaheuristic algorithms. For example, it is more robust against the choice of initial population and control parameters than PSO, ABC and others for continuous unconstrained optimization [27]. DS algorithm in [27] can only be used to solve box constrained optimization problems. Although application of DS to unconstrained optimization is well-established, so far few studies have focused on the application of DS to constrained optimization. In this paper, we will further develop this algorithm to solve generalized constrained optimization problems. To handle the constraints, the penalty function methods are always introduced. If the penalty parameter is a constant, this method is referred to as static penalty method. Otherwise, it is referred to as dynamic penalty method. In terms of static penalty, dynamic penalty is more desirable since the penalty parameter is adjusted dynamically. Different from the existing dynamic penalty method [28,29], we will introduce a novel S-type function to generate the dynamic penalty parameter. Comparing with the dynamic penalty method in [28], our proposed dynamic method achieves better numerical performances. Assorting to the penalty method, the original constrained optimization problem is approximated by a sequence of unconstrained optimization problems. Then, DS algorithm in [30] is applied to solve those unconstrained optimization problems. Thus, our proposed algorithm can be described as two main steps: penalty factor iteration and optimal solution iteration. In the penalty factor iteration, the penalty parameter is updated using an S-type threshold dynamic update scheme. While in the optimal solution iteration, a nonlinear unconstrained optimization with the penalty function is solved by DS. To show the performance of our proposed algorithm, two benchmark sets, CEC2006 and CEC2010, and four engineering design optimization problems have solved by our method as well as many swarm-based algorithms proposed in recent literatures. Numerical results show that our method can achieve better performance but with fewer function evaluations comparing with those algorithms.

2. Differential search algorithm

Differential Search (DS) algorithm is originally introduced to solve the problem of transforming the geocentric cartesian coordinates into geodetic coordinates in 2012. Comparison studies are carried out in [27] for continuous unconstrained optimization problems between the DS algorithm and eight widely used algorithms, including PSO, ABC, DE, and Gravitational Search Algorithm (GSA). The results show that DS algorithm in [27,31] is more powerful. DS algorithm also is successfully applied to circular antenna array design[32], needle roller bearing design[33] and multilevel color image thresholding [34]. DS algorithm simulates the Brownian-like random-walk movement carried out by an organism to migrate. In the migration movement, the migrating species of living beings constitute a superorganism, which contains a large number of individuals. Then, the superorganism starts to change its position by moving towards more fruitful areas. The movement of a superorganism can be described by a *Brownian-like random walk* model. Therefore, the simulation of the Brown motion is taken as a search strategy in DS.

2.1. Generation of the initial solution

In the process of solving optimization problem by DS, it is assumed that a population is made up of random outcomes of these artificial-superorganism migrations. An artificial-superorganism will migrate to the global minimum of the problem. During this migration, the artificial-superorganism examines whether some randomly selected positions are suitable temporary positions during the migration. If such a position is suitable to stopover temporarily during the migration, the members of the