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An adaptive gradient descent-based local search in memetic algorithm applied to optimal controller design

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ABSTRACT

Memetic Algorithm (MA) is a combination of Evolutionary Algorithms (EAs) and Local Search (LS) operators known as hybrid algorithms. In this paper, an efficient MA with a novel LS, namely Memetic Algorithm with Adaptive LS (MA-ALS), is proposed to improve accuracy and convergence speed simultaneously. In the core of the proposed MA-ALS, an adaptive mechanism is carried out in LS level based on the employment of specific group with particular properties, which is inspired from an elite selection process. Thus, the proposed adaptive LS can help MA to execute a robust local refinement. This methodology reduces computational costs without loss of accuracy. The algorithm is tested against a suite of well-known benchmark functions and the results are compared to GA and the two types of MAs. A permanent DC motor, a Duffing nonlinear chaotic system and a robot manipulator with 6 degree-of-freedom are employed to evaluate the performance of the proposed algorithm in optimal controller design. Simulation results demonstrate the feasibility of the algorithm in terms of accuracy and convergence speed.

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1. Introduction

Optimal control of nonlinear systems is amongst pivotal subjects in control engineering, such as solving problems in economics, chemical engineering and robotics. In classic optimal control theory, there exist nonlinear Hamilton–Jacobi–Bellman partial differential equations that are quite difficult to solve [7]. Accordingly, numerical methods need to be used such as Gradient Descents (GDs) and Iterative Dynamic Programming (IDP) for solving optimal control problems. Despite their usefulness, both GDs and IDP may get trapped in local optimum depending on the initial solution guess. Moreover, IDP suffers from high computational costs [34]. Another way of finding the optimal solution would be the Evolutionary Competition (EC). EC finds the optimal solution through cooperation and competition among the individuals of population [61]. The frequently used population-based EC methods include evolutionary strategies [62], Genetic Algorithm (GA) [20,38,53], Evolutionary Programming (EP) [42], clustering methods [35], Ant Colony Optimization (ACO) [15,41], Particle Swarm Optimization (PSO) [2–6,22,36,39] and chemical optimization paradigm [37]. Meanwhile, Evolutionary Algorithms (EAs) can be enhanced by combining existing algorithms that can be used for modeling and controlling of the processes with complex dynamical behavior [36,37,58]. Since EAs are population-based, a well balance between exploration and exploitation need to be utilized in order to find optimum solutions [11]. The exploration refers to the ability of investigating various unknown regions in the solution space to discover the global optimum. Whereas, the exploitation indicates the capability

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of the algorithm to refine a candidate solution to a local optimum, having already found in a region of interest. For instance, GA can explore a wide range of search space efficiently, while it does not have efficient exploitation ability. It means GA does not have a useful Local Search (LS) mechanism to accurately search near a good solution [16]. The performance of GA can be improved by incorporating different LS and traditional GAs, which is called Memetic Algorithm (MA) [17,28,40]. Indeed, MA is a combination of EAs and LS operators to obtain an efficient global search known as hybrid algorithms.

MAs have been successfully applied in wide areas of engineering fields [1,29,31,43,51,57,59,63,64] and the significance influence of LS on the performance of the search process of MAs has already been reported [8,13,19,21,23,24,47,50,53,65]. MAs are more efficient than the traditional EAs in many applications; however the method of designing a MA with a good performance is complicated. To design a competitive MA, as stated earlier the LS operators should be kept in a balance between exploration and exploitation. Here, a novel GD-based LS is introduced to improve the performance of MA in solving engineering optimization problems. The LS operator is employed to enhance the individuals' qualities efficiently in a local area. Accordingly, an adaptive type of LS is proposed with a mechanism that limits the number of selected individuals based on their fitness. As a result, the overall speed of LS is improved, since local search is only applied to the elite individuals and not on the whole population.

The main motivation of the proposed algorithm is to combine the ability of GA in global search and the accuracy of GD in local search by applying reasonable adaptive laws. The algorithm accomplishes global search over the whole search space through GA and the LS is performed by a GD-based algorithm. The LS has two significant parameters for each individual, namely the search neighborhood and the number of iterations. Herewith, at the beginning of the algorithm since there is no awareness about the solution, the elite society should be vast enough to cover the whole search space. For this phase, the search neighborhood is considered to be large and at the same time the number of gradient descent iterations need to be low. As the global search goes on, the elite society starts to become smaller and smaller. As a result, the boundary to search neighborhood will be shrunken. Thereafter, the LS implies to the specific group with particular properties, which is inspired from the elite selection process. In this way, the proposed algorithm is able to find an optimum solution more accurately.

The rest of the paper is organized as follows: Section 2 describes the optimization algorithms briefly. Section 3 presents the framework on the base of MA search scheme. The proposed MA-ALS algorithm is also described in details. Simulation results are presented in Section 4. Section 5 deals with the evaluation of MA-ALS via considering three real-world optimization problems. Finally, conclusion is drawn in Section 6.

2. Optimization algorithms

In this section, the basic principles of the optimization algorithms are briefly described, which are used in this paper.

2.1. GA

GA generates solutions to optimization problems using techniques inspired by natural evolution, such as inheritance, mutation, selection, and crossover. Only binary variables (genes) are used in the traditional GA, which form a string (chromosome). Original real numbers are generated by decoding the final binary digits after a utilization of binary-coded GA. On the other hand, all genes in a chromosome are real numbers in real-coded GA. Therefore, to solve practical engineering problems, it is preferred to use the real-coded GA instead of the binary-coded GA [10]. In spite of convergence to the global optimum, GA converges excessively slowly to find the global optimum with sufficient precision. The reason is the failure of GA in exploiting local information [58]. In the rest of the paper, GA refers to "real-coded GA".

2.2. GD-based LS

Gradient information of the objective function is consequential due to the dependency of a large number of widely-used deterministic algorithms on it such as steepest descent and Newton's method [33]. A relation between input and output of the functions in a gradient-based method must be established or approximated [14]. Although the first-order derivatives for some methods like steepest descent will suffice, the Newton's method requires second-order information [44]. Considering a pre-defined search direction $\Delta_k \in R^n$, the optimal step size α_k is explored:

$$F(x + \alpha_k \Delta_k) = \min_{\alpha}\{F(x + \alpha_k \Delta_k)\} \tag{1}$$

Steepest descent method introduced by Curry [12] is one of the simplest gradient methods. This method is easy to implement, but it usually converges to a local optimum. It follows from the fact that the gradient vector points to the direction of fastest increase in the value of the function. The search points are iteratively generated by stepping in the opposite direction of the gradient. The current search point x_k is generated as

$$x_{k+1} = x_k - \alpha_k \nabla f(x_k)/\|\nabla f(x_k)\| \tag{2}$$

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