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Reliability-based design optimization with discrete design variables and non-smooth performance functions: AB-PSO algorithm

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ABSTRACT

The purpose of reliability-based design optimization (RBDO) is to find a balanced design that is not only economical but also reliable in the presence of uncertainty. Practical applications of RBDO involve discrete design variables, which are selected from commercially available lists, and non-smooth (non-differentiable) performance functions. In these cases, the problem becomes an NP-complete combinatorial optimization problem, which is intractable for discrete optimization methods. Moreover, the non-smooth performance functions would hinder the use of gradient-based optimizers as gradient information is of questionable accuracy. A framework is presented in this paper whereby subset simulation is integrated with a new particle swarm optimization (PSO) algorithm to solve the discrete and non-smooth RBDO problem. Subset simulation overcomes the inefficiency of direct Monte Carlo simulation (MCS) in estimating small failure probabilities, while being robust against the presence of non-smooth performance functions. The proposed PSO algorithm extends standard PSO to include two new features: auto-tuning and boundary-approaching. The former feature allows the proposed algorithm to automatically fine tune its control parameters without tedious trial-and-error procedures. The latter feature substantially increases the computational efficiency by encouraging movement toward the boundary of the safe region. The proposed auto-tuning boundary-approaching PSO algorithm (AB-PSO) is used to find the optimal design of a ten-bar truss, whose component sizes are selected from commercial standards, while reliability constraints are imposed by the current design code. In multiple trials, the AB-PSO algorithm is able to deliver competitive solutions with consistency. The superiority of the AB-PSO algorithm over standard PSO and GA (genetic algorithm) is statistically supported by non-parametric Mann–Whitney U tests with the p-value less than 0.01.

1. Introduction

Reliability-based design optimization (RBDO) is concerned with designing a structure to optimize an objective function, with uncertainty about whether a given reliability threshold is met. This problem is of paramount importance to a wide spectrum of engineering fields, especially civil engineering [1]. The most common objective function is the minimization of material cost or weight. For many practical situations where customization is expensive, the design variables are, by nature, discrete as their values can only be selected from a commercially available set, such as the diameter of tubes, thickness of plates, or cross-section of steel beams [19]. Furthermore, computations of reliability constraints in real-world applications often involve highly nonlinear, non-smooth, and non-differentiable performance functions, which are needed to relate the structural state (failure or safe) to uncertainty [38,41]. The RBDO problem with discrete design variables and non-smooth performance functions is the target of the present study.

The complexity of the considered RBDO problem is three-fold. First, the solution space is discrete; the problem hence belongs to the category of combinatorial optimization, known as NP-complete. Existing discrete optimization algorithms require, in worst case, an exponential amount of time, and therefore are impractical for all but very small instances [29]. Second, the non-smoothness of performance functions renders conventional gradient-based optimizers ineffective as they would stall due to gradient inaccuracy and fail to converge [39]. Popular gradient-based optimizers include sequential quadratic programming (SQP) or generalized reduced gradient algorithms (GRG2). Third, the nonlinearity and non-smoothness of the reliability criteria may diminish the accuracy of approximation methods, e.g., first-order or second-order reliability methods, in estimating failure probabilities. By contrast, Monte Carlo simulation (MCS) is insensitive to the types of reliability criteria. Yet, MCS is computationally intensive as it needs a large number of samples to evaluate small failure probabilities.

To address all the foregoing concerns, the present study develops a framework to integrate a new gradient-free optimization method with an efficient simulation procedure. The proposed method is a modified particle swarm optimization (PSO) algorithm with two new features: being auto-tuning and boundary-approaching. The auto-tuning feature

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