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ORIGINAL ARTICLE

A Three-bar Truss Design using Single-solution Simulated Kalman Filter Optimizer

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ABSTRACT –Three-bar truss is a structure that is important in the field of civil engineering. Design of the three-bar truss is thus an interesting problem in engineering. Metaheuristic approach has been employed to get near-optimal solution of this problem. A study to investigate the effectiveness of a new single-solution simulated Kalman filter (ssSKF) algorithm in three-bar truss design is presented in this paper. The solution obtained by the ssSKF is as good as hybrid lightning search algorithm-simplex method and better than solutions produced other algorithms in literature.

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Introduction

Design optimization can be defined as the process of finding the optimal parameters, which yield minimum or maximum value of an objective function and at the same time satisfy a particular set of constraints. This can be solved by an exact method or approximation method. The exact method ensures an optimal solution but the cost of this method can be very huge as the intricacy to compute increases. The approximate method is more efficient in terms of the utilization of time and memory [1]. An approximation method ensures a bounded solution that determines how close the solution acquired from the ideal optimal, however the optimum solution is not always guaranteed, especially for complicated problems. Optimization algorithms are among the well-known approximation methods.

The simulated Kalman filter (SKF) [2] is one of the optimization algorithms that has been developed based on Kalman filtering. The SKF can operates using many agents or one agent only. If many agents are used, the SKF is called population-based SKF [3], whereas if one agent is used, the SKF is called single-solution SKF (ssSKF) [4]. To date, the population-based SKF has been applied in solving many practical problems [5-17], however, applications of ssSKF is still lacking [18]. In this paper, the usefullness of ssSKF is demonstrated by solving a three-bar truss design problem.

The three-bar truss design problem is firstly introduced by Ray and Saini [19]. The desired placement of the bars is shown in Figure 1. The objective of the design is to minimize the total weight of the bars subjected to stress, deflection, and buckling constraints by finding the cross sectional areas. This problem has been solved by many researchers in literature. For example, Tsai has employed a method to solve nonlinear fractional programming [20]. Ray and his colleagues solved the design problem using swarm method [19] and society and civilization optimization algorithm [21]. On the other hand, Gondomi *et al*. proposed a new cuckoo search algorithm and subsequently solve the three-bar truss design problem [22]. Other than that, differential evolution [23], hybrid particle swarm optimization with differential evolution [24], mine blast algorithm [25], moth flame algorithm [26], and hybrid lighting search with simplex method [27], have been employed as well.

Design of three-bar truss

Mathematically, to minimize the weight of three-bar truss according to [19], an objective function is formulated as follows:

$$\text{Minimize } f(\boldsymbol{X}) = (2\sqrt{2}x_1 + x_2) \times l \tag{1}$$

subject to

$$g_1(x) = \frac{\sqrt{2}x_1 + x_2}{\sqrt{2}x_1^2 + 2x_1 x_2} P - \sigma \leq 0 \tag{2}$$

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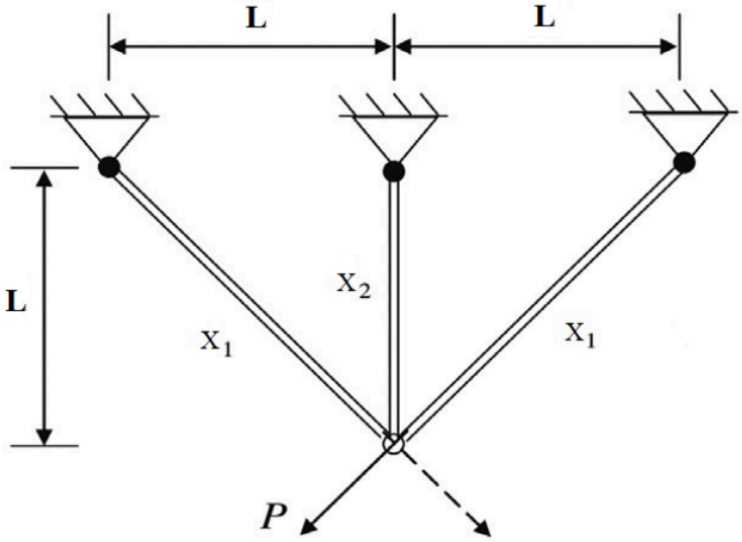

Figure 1. The three-bar truss [19].

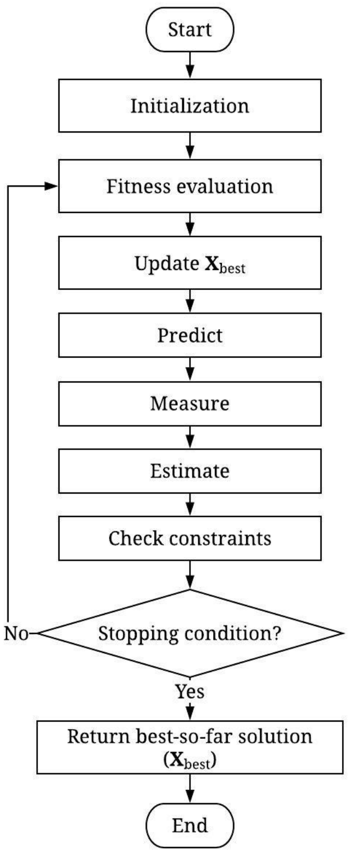

Figure 2. Flowchart of the ssSKF algorithm [4].

$$g_2(x) = \frac{x_2}{\sqrt{2}x_1^2+2x_1\,x_2} P - \sigma \leq 0 \tag{3}$$

$$g_3(x) = \frac{1}{\sqrt{2}x_2 + x_1} P - \sigma \leq 0 \tag{4}$$

where $0 \leq x_1, x_2 \leq 1$, $l = 100$ cm, $P = 2$ KN/cm^2, and $\sigma = 2$ KN/cm^2.

The Single-solution Simulated Kalman Filter for the Three-bar Truss Design

The flowchart of the single-solution simulated Kalman filter (ssSKF) algorithm [4] is shown in Figure 2. The algorithm begins with random initial solution, $X(0)$. Initial error covariance, $P(0)$, is set to a normally distributed random number. After that, fitness according to equation (1) is calculated. Then, the best-so-far solution, $\boldsymbol{X}_{best}$, is updated.

During prediction, the following equations are used to predict the optimum solution:

$$\boldsymbol{X}^d(t|t+1) \sim U\left[\boldsymbol{X}_{best}^d - \delta_t, \boldsymbol{X}_{best}^d + \delta_t\right] \tag{5}$$

$$P^d(t|t+1) = P^d(t) + randn^d \tag{6}$$

$$\delta_t = e^{-\frac{\alpha \times t}{t_{Max}}} \times \delta_0 \tag{7}$$

$$\delta_0 = \max(|\text{lowerlimit}|, |\text{upperlimit}|) \tag{8}$$

where t_{Max} is the maximum number of iterations and $randn^d$ is a normally distributed random number.

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Table 1. Experimental setting.

Variable	Value
Maximum iterations	200 - 20,000,000
α	5

Table 2. Experimental results.

Maximum iteration	*f*(*X*)
20,000,000	263.8958
2,000,000	263.8960
200,000	263.9052
20,000	263.8979
2,000	264.4205
200	264.2370

Table 3. Results comparison.

Reference	Method	x_1	x_2	*f*(*X*)
Tsai [20]	A method to solve nonlinear fractional programming	0.788	0.408	263.68
Ray and Saini [19]	Swarm strategy	0.795	0.395	264.3
Ray and Liew [21]	SC	0.7886210370	0.4084013340	263.8958466
Gandomi *et al.* [22]	CS	0.78867	0.40902	263.9716
Zhang *et al.* [23]	DEDS	0.78867513	0.40824828	263.8958434
Liu *et al.* [24]	PSO-DE	0.7886751	0.4082482	263.8958433
Sadollah *et al.* [25]	MBA	0.7885650	0.4085597	263.8958522
Mirjalili [26]	MFO	0.788244770931922	0.409466905784741	263.895979682
Lu *et al.* [27]	LSA-SM	0.7886136	0.4084224	**263.8958**
Present study	ssSKF	0.7887	0.4083	**263.8958**

After that in measurement step, the simulated measurement value, $\mathbf{Z}^d(t)$, is computed as follows:

$$\boldsymbol{Z}^d(t) = \boldsymbol{X}^d(t|t+1) + \Delta \tag{9}$$

where

$$\Delta = sin(rand^d \times 2\pi) \times \left|\boldsymbol{X}^d(t|t+1) - \boldsymbol{X}^d_{best}\right| \tag{10}$$

Finally, during the estimation step, the solution and error covariance estimates for the next iteration are calculated as follows.

$$K^d(t) = \frac{P^d(t|t+1)}{P^d(t|t+1) + rand^d} \tag{11}$$

$$\mathbf{X}^d(t+1) = \mathbf{X}^d(t|t+1) + \gamma \tag{12}$$

$$\gamma = K^d(t) \times (\mathbf{Z}^d(t) - \mathbf{X}^d(t|t+1)) \tag{13}$$

$$P^d(t+1) = (1 - K^d(t)) \times P^d(t|t+1) \tag{14}$$

A solution generated by equation (12) is accepted if all the constraints computed based on equations (2-4) are valid. This process continues until the maximum number of iterations. Note that ssSKF requires only α and the maximum number of iterations as the tuning parameter.

Experiment, Result, and Discussion

Table 1 shows the parameter setting of the ssSKF. Based on the experimental setting parameters, $f(\boldsymbol{X})$ = 263.8958 was the best fitness obtained where x_1 and x_2 values are 0.7887 and 0.4083, respectively. Table 2 shows different fitness values when different maximum iterations are applied.

Table 3 shows the results obtained against other results reported in literature based on different algorithms. Those algorithms are a method to solve nonlinear fractional programming [20], swarm method [19], society and civilization optimization algorithm [21], cuckoo search algorithm [22], differential evolution [23], hybrid particle swarm optimization with differential evolution [24], mine blast algorithm [25], moth flame algorithm [26], and hybrid lighting search with simplex method [27]. The comparison shows that the design variables obtained by the ssSKF is as good as the design variables obtained by the hybrid lighting search with simplex method. In this particular case, both the ssSKF and the hybrid lighting search with simplex method able to find design variables better than the rest of the algorithms.

Note that the ssSKF algorithm, in this study, requires as many as 20,000,000 iterations to get good results. Since the ssSKF algorithm operates only using one agent, this is still acceptable.

Conclusions

This paper study the use of ssSKF to find the minimum weight of a three-bar truss. The performance of the ssSKF have been compared against other algorithms reported in literature. The results showed that in the tree-bar truss design, the ssSKF is on par with the hybrid lighting search with simplex method and able to outperform other eight algorithms.

In the future, the ssSKF algorithm will be further employed to solve other engineering design problem such as cantilever beam, pressure vessel, and welded beam design.

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