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Application of Subtraction Average-Based Optimizer to Selected Electrical and Mechanical Engineering Problems

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Abstract: Summary Mechatronics engineering typically involves dealing with challenges related to designing and upkeeping mechanical and electrical systems. The subtractive averaging-based optimization algorithm is a commonly used method for minimizing system errors by iteratively adjusting parameters to enhance system performance and stability. In this thesis, the advantages and disadvantages of this optimization algorithm in solving the corresponding problems are investigated by applying the subtractive averaging optimizer to some electromechanical engineering problems. The final optimization results in solving Gas Transmission Compressor Design and Planetary Gear Train Design Optimization are very similar to the theoretical values, but for Optimal Setting of Droop Controller for Minimization of Reactive Power Loss in Islanded Microgrids problem the optimization values are more different from the theoretical values. It was found that the subtractive averaging optimizer is beneficial for solving electromechanical engineering problems in some specific problems.

1. Introduction

Mechatronics engineering emerges as is a new multifaceted, rooted in the synergy of mechanical engineering, and computer applications .It also draw from cybernetics and information science. Mechatronic engineering holds significant importance in today's industries. Its scope encompasses the design, fabrication, control and upkeep of mechanical and electrical systems. As science and technology advance, mechatronics engineering evolves, furnishing crucial support to various industries. Electromechanical engineers, in particular, are expected to possess a comprehensive skill set spanning, mechanical design, circuit principles, control systems, and sensor technology. In a way, solving Mechatronics engineering problems are a matter of engineers continuously optimizing the product to achieve an even better state.

Metaheuristics belong to a category of optimization algorithms that utilize heuristic ideas and strategies to solve complex optimization problems. These algorithms blend stochastic and local search methodologies, aiming to provide an optimal solution, within an acceptable computational cost. Every algorithm comes with its unique search strategy and parameter configurations. Meta-heuristic algorithms usually include steps such as population initialization, individual evaluation, exploration, exploitation, and population update. Through iterative refinement, metaheuristic algorithm continuously improved and optimized their performance to yield superior solutions. Many different metaheuristic algorithms exist, such as: (1). Genetic Algorithms[1-2] are used to optimize the solution of a problem by simulating the process of natural selection using genetic coding and genetic manipulation;. (2).Particle Swarm Optimization(PSO)is an algorithm that mimics the movement of a group of birds.(1)Using collaboration and information sharing among individuals, it seeks the best solution;(2)Drawing inspiration from the foraging behavior of ants, the Ant Colony Optimization algorithm simulates the release of pheromones to find the optimal path;(3)The Artificial Immune System mimics human immune system processes to discover optimal solutions[3];(4)The Ant Lion Optimizer mirrors the predatory behavior of ant lions, using predation and avoidance mechanisms to pinpoint optimal solutions[4-5].

These metaheuristic algorithms exhibit unique traits and applicability across various optimization problems domains, allowing for tailored selection based on specific problem characteristics. The metaheuristic algorithms discussed earlier exhibit certain limitations including(1)complex parameter tuning needs, which can be difficult to determine optimal settings and may impact algorithm performance; and(2)instances of slow convergence and getting stuck in local optimal solutions, potentially diminishing efficiency in specific scenarios.

To overcome these limitations, a novel evolution-based approach for solving optimization problems, known as the Subtractive Average-Based Optimizer (SABO), has been proposed by researchers [9].The SABO algorithm is based on the subtractive averaging concept, where search agents in the population update their positions by subtracting the average position from each individual's current position. This technique has been found to deliver superior performance compared to other metaheuristics, while requiring fewer parameters .Given the superiority of the Subtractive Averaging-Based Optimizer (SABO), this paper employs it to tackle a range of problems in the field of electromechanical engineering. The rest of this paper is organized as follows Section 2 describes the mathematical model of the SABO; Section 3 covers experimental simulations and result analysis; and Section 4 provides conclusions and future research directions stemming from this study.

2. Subtraction Average-Based Optimizer

The Subtraction Average-Based Optimizer is a mathematically related optimization algorithm proposed in 2023. It is distinguished by its high optimality and fast convergence, achieved through subtractive average of individuals to update the position of group members within the search space. During population initialization, each individual's position is initialized to:

$$z_{i,j} = ly_j + \mathrm{r} \bullet \left(uy_j - ly_j \right) \tag{1}$$

where $z_{i,j}$ is the individual; ly_j is the lower bound of the search for superiority; uy_j is the upper bound on the search for superiority; r is a randomized number between [0,1].

The design of the SABO is inspired by mathematical concepts such as averages, differences in search agent positions, and the sign of the difference between two objective function values. The SABO algorithm incorporates the mean position of all search agents when updating their positions, rather than solely relying on the positions of the top-performing or lowest-performing search agents. While not a novel concept, SABO's approach to calculating the arithmetic mean is distinct due to its reliance on a special subtraction operation "$-_v$". i.e., search agent B subtracts v from search agent A.

$$A -_v B = sign\left(g\left(A \right) - g\left(B \right) \right)\left(A - \vec{v} * B \right) \tag{2}$$

Where is a set of vectors that randomly generate data from the set{1，2}，and are the fitness values of individuals and. $_v$ $g(A)$ $g(B)$ A B

In the proposed SABO, the displacement of any search agent D_i is computed by the arithmetic mean of the v subtraction of each search agent D_j. The displacement of any search agent D_i is computed by the arithmetic mean of the v-subtraction of each search agent D_j. $j = 1, 2.....N$ from search agent D_i .Hence, utilize Equation(3)to calculate the updated position of every search agent.

$$D_i^{new} = D_i + \vec{r_i} * \frac{1}{N} \sum_{j=1}^{N} (D_i - vD_j), i = 1, 2...., N \tag{3}$$

Where r is a random number between [0,1]; N is the total number of individuals. D^{new} is the new position after the update, if the updated position is better than replace the original position, otherwise leave it as it is:

$$D_i = \begin{cases} D_i^{new}, F_i^{new} < F_i \\ D_i, else \end{cases} \tag{4}$$

3. Numerical experiments

3.1 Preparation

The algorithms were developed using MATLAB R2023b on a 64-bit Windows 11 system. They utilize a population size of 100 and a maximum of 100 function iterations.

3.2 Results and discussion

3.2.1 Planetary Gear Train Design Optimization Problem

The issue can be characterized as the objective of reducing the highest level of errors in the gear ratio, a critical element that impacts the efficiency of vehicles, by establishing the total count of gear teeth for an automatic planetary transmission system. This task involves optimizing six integer variables and 11 constraints that account for various geometric and assembly restrictions

Minimize:

$$f(\bar{x}) = \max |i_k - i_{0k}|, k = \{1, 2...R\} \tag{5}$$

Where,

$$i_1 = \frac{N_6}{N_4}, i_{01} = 3.11, i_2 = \frac{N6(N_1N_3 + N_2N_4)}{N1N3(N_6 - N_4)}, i_{0R} = -3.11,$$
$$I_R = -\frac{N_2N_6}{N_1N_3}, i_{02} = 1.84, \bar{x} = \{p, N_6, N_5, N_4, N_3, N_2, N_1, m_2, m_1\} \tag{6}$$

Subject to:

$$g_1\left(\bar{x}\right) = m_3\left(N_6 + 2.5\right) - D_{\max} \le 0$$
$$g_2\left(\bar{x}\right) = m_1\left(N_1 + N_2\right) + m_1\left(N_2 + 2\right) - D_{\max} \le 0$$
$$g_3\left(\bar{x}\right) = m_3\left(N_4 + N_5\right) + m_3\left(N_5 + 2\right) - D_{\max} \le 0$$
$$g_4\left(\bar{x}\right) = \left|m_1\left(N_1 + N_2\right) - m_3\left(N_6 - N_3\right)\right| - m_1 - m_3 \le 0$$
$$g_5\left(\bar{x}\right) = -\left(N_1 + N_2\right)\sin\left(\pi/p\right) + N_2 + 2 + \delta_{22} \le 0$$
$$g_6\left(\bar{x}\right) = -\left(N_6 - N_3\right)\sin\left(\pi/p\right) + N_3 + 2 + \delta_{33} \le 0$$
$$g_7\left(\bar{x}\right) = -\left(N_4 + N_5\right)\sin\left(\pi/p\right) + N_5 + 2 + \delta_{55} \le 0 \tag{7}$$

$$g_8\left(\bar{x}\right) = \left(N_3 + N_5 + 2 + \delta_{35}\right)^2 - \left(N_6 - N_3\right)^2 - \left(N_4 + N_5\right)^2 + 2\left(N_6 - N_3\right)\left(N_4 + N_5\right)\cos\left(\frac{2\pi}{p} - \beta\right) \le$$
$$g_9\left(\bar{x}\right) = N_4 - N_6 + 2N_5 + 2\delta_{56} + 4 \le 0$$
$$g_{10}\left(\bar{x}\right) = 2N_3 - N_6 + N_4 + 2\delta_{34} + 4 \le 0$$
$$h_1\left(\bar{x}\right) = \frac{N6 - N4}{p} = \text{integer}, \tag{8}$$

Where,

$$\delta_{22} = \delta_{33} = \delta_{55} = \delta_{35} = \delta_{56} = 0.5.$$
$$\beta = \frac{\cos^{-1}\left(\left(N_4 + N_5\right)^2 + \left(N_6 - N_3\right)^2 - \left(N_3 + N_5\right)^2\right)}{2\left(N_6 - N_3\right)\left(N_4 + N_5\right)}, D_{\max} = 220, \tag{9}$$

With bounds:

$$p = \left(3, 4, 5\right),$$
$$m_1 = \left(1.75, 2.0, 2.25, 2.5, 2.75, 3.0\right),$$
$$m_3 = \left(1.75, 2.0, 2.25, 2.5, 2.75, 3.0\right), \tag{10}$$

$$17 \le N_1 \le 96, \qquad 14 \le N_2 \le 54, 14 \le N_3 \le 51$$
$$17 \le N_4 \le 46, \qquad 14 \le N_5 \le 51, 48 \le N_6 \le 124, \tag{11}$$

and N_i =integer.

The results demonstrate that: The optimal solution of SABO on Planetary Gear Train Design Optimization Problem[6] is [0.5371, 0.5309, 0.5270, 0.5819, 0.5324] The final minimum value obtained is 0.5270 and the theoretical minimum value is 0.5258. Therefore the SABO excelled in solving the problem.

3.2.2 Gas Transmission Compressor Design

To ensure the smooth transportation of natural gas from its source to its destination, compressors play a crucial role in natural gas transmission systems. These compressors are tasked with compressing the natural gas during transmission, ensuring its smooth flow through the pipeline. The design process involves careful selection of the appropriate compressor, optimal layout, and piping design to achieve efficient and stable transportation of natural gas. The problem involves 4 integer variables and 1 constraint, encompassing various geometric and assembly limitations. Thus, the objective is to determine the optimal values for the 4 variables while adhering to the constraint, with the aim of minimizing the maximum error in the gear ratio. Mathematically, this problem can be defined as follows:

Minimize:

$$f\left(\bar{x}\right)=8.61\times10^{5}x_1^{1/2}x2x_3^{-2/3}x_4^{-1/2}+3.69\times10^{4}x3+7.72\times10^{8}x_1^{-1}x_2^{0.219}-765.43\times10^{6}x_1^{-1} \tag{12}$$

Subject to:

$$x_4x_2^{-2}+x_2^{-2}-1\leq 0 \text{ ,} \tag{13}$$

With bounds:

$$\begin{aligned}&20\leq x_1\leq 50,\\&1\leq x_2\leq 10,\\&20\leq x_3\leq 50,\\&0.1\leq x_4\leq 60\end{aligned} \tag{14}$$

Results show: The optimal solution of SABO on Gas Transmission Compressor Design[7] problem is [3.1488e+06, 2.9956e+06, 3.1490e+06, 3.1153e+06, 3.1459e+06] The final minimum value obtained is 2.9956e+06, and the theoretical minimum value is 2.9649E+06.Therefore，the SABO excels in addressing this issue.

3.2.3 Optimal Setting of Droop Controller for Minimization of Reactive Power Loss in Islanded Microgrids

The main aim of this problem is to reduce reactive losses by adjusting the droop parameters. It can be represented as a constrained optimization problem in which the goal is to determine the optimal values for 7 integer variables while satisfying 4 constraints that account for various geometric and assembly limitations. The end goal is to reduce the maximum error in the gear ratio as much as possible.

Minimize:

$$f=\sum_{i=1}^{N}Q_i \tag{15}$$

Subject to:

$$\begin{aligned}
&\sum_{i=1}^{N}\left(G_{k,i}V_{r,i}-B_{ki}V_{m,i}\right)-\frac{P_kV_{r,k}+Q_kV_{m,k}}{\left(V_{r,k}\right)^2+\left(V_{m,k}\right)^2}=0,\\
&\sum_{i=1}^{N}\left(B_{k,i}V_{r,i}-G_{ki}V_{m,i}\right)-\frac{P_kV_{m,k}+Q_kV_{r,k}}{\left(V_{r,k}\right)^2+\left(V_{m,k}\right)^2}=0,\\
&P_k-Cp_k\left(w_k^*-w\right)+P_{l,k}=0,\\
&P_k-Cq_k\left(V_k^*-\sqrt{\left(V_{r,k}\right)^2+\left(V_{m,k}\right)^2}\right)+Q_{l,k}=0
\end{aligned} \tag{16}$$

With bounds:

$$\begin{aligned}
&V_{\min}\le V_{r,k},V_{m,k}\le V_{\max}\\
&P_{\min}\le P_k\le P_{\max}\\
&Q_{\min}\le Q_k\le Q_{\max}\\
&Cp_{\min,k}\le Cp_k\le Cp_{\max,k}\\
&Cq_{\min,k}\le Cq_k\le Cq_{\max,k}\\
&w_{\min}\le w\le w_{\max}
\end{aligned} \tag{17}$$

The findings indicate that the SABO offers an optimal solution of [0.0958, 0.1866, 0.1014, 0.1106, 0.0674] for minimizing reactive power loss in islanded microgrids by setting the droop controller[8-9]. The final minimum value obtained is 0.0674, slightly deviating from the theoretical minimum value of 8.0421E-02. Therefore, the SABO shows mediocre performance in addressing this issue.

4. Conclusions and Future Works

In this paper, we introduce the mathematical model of the Subtraction Averaging-Based Optimizer (SABO) and demonstrate its effectiveness in optimizing a specific electromechanical engineering problem. In this study, the SABO algorithm stands out for its exceptional performance in two of the three problems examined, namely the Planetary Gear Train Design Optimization Problem and the Gas Transmission Compressor Design. The optimal values achieved with the SABO algorithm closely align with the theoretical optimal values for these problems. Nevertheless, the substantial disparity between the optimal value and the theoretical value observed in the Optimal Setting of Droop Controller for Minimization of Reactive Power Loss in Islanded Microgrids problem suggests that the optimization algorithm may be more effective in addressing the other two issues. Therefore, we suggest that the SABO algorithm be applied more broadly to more complex electromechanical engineering problems. Further experimentation is needed to improve the algorithm's performance for specific problems, thereby enhancing its applicability in the field of science and technology.

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