Research on performance seeking control based on Beetle Antennae Search algorithm

Qiangang Zheng, Dewei Xiang, Juan Fang, Yong Wang, Haibo Zhang and Zhongzhi Hu

Abstract
A novel performance seeking control) method based on Beetle Antennae Search algorithm is proposed to improve the real-time performance of performance seeking control. The Beetle Antennae Search imitates the function of antennae of beetle. The Beetle Antennae Search has better real-time performance because of the objective function only calculated twice in Beetle Antennae Search at each iteration. Moreover, the Beetle Antennae Search has global search ability. The performance seeking control simulations based on Beetle Antennae Search, Genetic Algorithm and particle swarm optimization are carried out. The simulations show that the Beetle Antennae Search has much better real-time performance than the conventional probability-based algorithms Genetic Algorithm and particle swarm optimization. The simulations also show that these three probability-based algorithms can get better engine performance, such as more thrust, less specific fuel consumption and less turbine inlet temperature.

Keywords
Aero-engine control, performance seeking control, real time, probability-based algorithms, Beetle Antennae Search

Introduction
The coupling relationship between the controllers of aircraft and engine is seldom taken into account in the conventional controller systems design process. However, the coupling relationship between these two parts is becoming increasingly close with aerospace technology developments. The aircraft performances are always affected by the this coupling relationship, which may increase over-flow resistance, after-body drag and so on. Therefore, the performance seeking control (PSC) is proposed by NASA (National Aeronautics and Space Administration). PSC seeking some best engine performance for a specific flight mission, such as maximum thrust, minimum turbine temperature or minimum specific fuel consumption. Meanwhile, the operating engine should operate within all limits. The on-board model and optimization algorithm are the two key points to realize PSC. The main job of this paper is focus on the second one—the optimization algorithm.

NASA developed PSC based on linear programming (LP) in the 1990s, for better engine performance. However, the control error is inevitably existing if the engine model is linearized due to the strong nonlinear characteristic of engine. Therefore, some scholars proposed a series of PSC optimization algorithms, such as MAPS (Model-Assisted Pattern Search), SQP (Sequential Quadratic Programming), PSMA (Particle Self-Migrating Algorithm), GA (Genetic Algorithm), PSO (particle swarm optimization), IA (Interval Analysis). During these algorithms, the probability-based algorithms, such as GA, PSO, make engine get better engine performance. The main reason is that the engine is a strong nonlinear object and has many local optimum values. The probability-based algorithms have strong search ability for this problem. However, the probability-based algorithms always have bad real-time performance. Inspired by the searching behavior of beetles which imitates the function of antennae, Jiang proposed Beetle Antennae Search (BAS). The objective function only calculated twice in BAS at each iteration. That is why the
BAS has better real-time performance and has global search ability. For these, a new PSC method based on BAS is proposed. The BAS is a simplicity, flexibility and local optimum avoidance optimization algorithm. The simulations show that the BAS optimization algorithm has better real-time performance than the conventional optimization algorithms—GA and PSO. The PSC control structure is shown in Figure 1. The PSC mainly consists of digital electronic engine controller, digital flight controller, aero-engine, nonlinear conversion module and PSC calculation module. The controlled plant is component-level model (CLM) which has highly static and dynamic modeling accuracy. Based on different flight missions, a pilot can select different PSC modes. For a special PSC mode, the best control variables can be optimized by the PSC calculation module. It can be seen that, to realize PSC, the most important part is the PSC calculation module, which mainly includes two parts—on-board model and optimization algorithm. The on-board model of this paper is the CLM, and the work about optimization algorithm will be mainly focused in this paper. The details will be introduced as follows.

The principle of PSC

The optimization problem of maximum thrust, minimum specific fuel consumption and minimum turbine inlet temperature could be described as follows.

The maximum thrust $F$ mode is always used in accelerating or climbing stage and can be described as follows

$$\max \ F \quad \text{s.t.} \quad \begin{align*}
    u_{\min} &\leq u \leq u_{\max} \\
    N_f &\leq N_f, N_c &\leq N_c, \\
    S_{mf} &\geq S_{mf}, S_{mc} &\geq S_{mc}, \\
    T_4 &\leq T_4, \max
\end{align*}$$

Minimum specific fuel consumption $S_{fc}$ mode can be described as follows

$$\min \ S_{fc} \quad \text{s.t.} \quad \begin{align*}
    F_i &= \text{const}; T_4 \leq T_4, \max \\
    N_f &\leq N_f, N_c &\leq N_c, \\
    S_{mf} &\geq S_{mf}, S_{mc} &\geq S_{mc}, \min
\end{align*}$$

For extending engine service life, the minimum turbine inlet temperature $T_4$ is developed as

$$\min \ T_4 \quad \text{s.t.} \quad \begin{align*}
    F_i &= \text{const} \\
    N_f &\leq N_f, N_c &\leq N_c, \\
    S_{mf} &\geq S_{mf}, S_{mc} &\geq S_{mc}, \min
\end{align*}$$

The principle of BAS

The BAS is a meta-heuristic optimization algorithm. As shown in Figure 2(a), longhorn beetles are characterized by extremely long antennae. The fundamental functions of these two antennae are finding prey odors and obtaining the potential suitable mate sex pheromone. As shown in Figure 2(b), the beetle searches nearby area randomly by antennae. The beetle searching behavior can be described as an objective function to be optimized.

The BAS is proposed to solve the following optimization problem

$$\min f(x)$$

The PSC is the constrained optimization problem. Therefore, the penalty function is adopted here as follows
\[
\min_{x} J_{\text{mod}} = J + \varepsilon \| \mathbf{p} \|^2
\]  
(5)

where \( J \) denotes the unmodified optimization objective of equations (1)-(3), \( \varepsilon \gg 0 \), \( \mathbf{p} \) is the weights vector on the constraint violations. The BAS is adopted to solve the unconstraint problem.

Define a random beetle searching direction as follows

\[
\vec{b} = \text{rnd}(k, 1) / \| \text{rnd}(k, 1) \| \quad (6)
\]

where \( k \) is the domain dimension, \( \text{rnd}(\bullet) \) presents a random function. Denote the searching behaviors of these two antennae as follows

\[
x_1 = x' + d' \vec{b} \\
x_2 = x' - d' \vec{b}
\]  
(7)

where \( x' \) is the current position of beetle, \( x_1 \) and \( x_2 \) denote the position of these two antennae, \( d' \) is sensing length of antennae.

The searching behavior of beetle can be described as follows

\[
x^{t+1} = x' + \delta \text{sign}(f(x_2) - f(x_1))
\]  
(8)

where \( \delta \) is the step size, \( \text{sign}(\bullet) \) is a sign function. The algorithm steps of BAS are shown as follows. For more details, Jiang and Li\textsuperscript{13,14} and Wang and Chen\textsuperscript{15} can be referenced.

### Simulation and analysis of the PSC

At present, the most popular probability-based optimization methods in PSC are GA and PSO. Therefore, there are three PSC simulations based on BAS, GA and PSO which are carried out, respectively, to verify the real-time performance of the proposed optimization algorithm. For the sake of narrative, these three simulations are named PSC I, PSC II and PSC III in the following, respectively. The operation limits of engine are given in Table 1.

As shown in Figures 3–8, the simulations of maximum \( F \) mode, minimum \( S_{fc} \) mode and minimum \( T_4 \)
mode are conducted at the cruise flight envelop $H = 8-12$ km, $Ma = 0.7-1.5$. Figures 3–5 show the real-time simulations of BAS, GA and PSO, respectively. The running environment of these three programs are identical. The computer is ASUS with Windows 7 Ultimate (sp1 x64), Intel(R) Core(TM) i7-7700 and 8GB RAM. The software is Matlab 2016b run. It can be seen that the program running times of maximum $F$, minimum $Sfc$ and minimum $T_4$ of BAS are most less than 0.6 s. In contrast, the program running times of maximum $F$ of GA are almost more than 2 s. The program running times of maximum $F$ of PSO are almost more than 1 s. In particular, in the minimum $Sfc$ and minimum $T_4$, the program running times of these two PSC modes of GA and PSO are almost more than 3 s. Therefore, the proposed method has better real-time performance.

Figures 6–8 give the changes of $F$, $Sfc$, $T_4$ after executing the program of maximum $F$, minimum $Sfc$ and minimum $T_4$, respectively. It can be seen from Figure 6 that the change of $F$ decreases with the increase of Mach number. The reason is that the turbine inlet temperature will increase rapidly with the increase of the Mach number, which results in the increase in the inlet temperature of engine and turbine. In this case, with the increase of the Mach number, the engine will have less potential. The largest change of $F$ reaches more than 20%. It can be seen from Figure 7 that the decrease of $Sfc$ is almost more than 4%. It can be seen from Figure 8 that the decrease of $T_4$ is more than 20K. It also can be seen from Figures 6–8 that the BAS, GA and PSO have the almost same optimization ability.

Conclusion

A new PSC method based on BAS is proposed in this paper. The BAS has better real-time performance and has global search ability on the optimization problem. The simulations of PSC based on the BAS, PSO and GA are carried out. The results show that the BAS has much better real-time performance than the conventional probability-based algorithms GA and PSO. The program running times of maximum $F$, minimum $Sfc$ and minimum $T_4$ of BAS are most less than 0.6 s. In contrast, the program running times of GA and PSO are almost more than 3 s. Moreover, these three probability-based algorithms can get more thrust, smaller turbine inlet temperature and less specific fuel consumption. After executing the program of maximum $F$, minimum $Sfc$ and minimum $T_4$, the largest change of $F$ reaches more than 20% in the subsonic...
Figure 6. The increase of $F$ in maximum thrust mode: (a) BAS, (b) GA and (c) PSO.

Figure 7. The decrease of $S_{fc}$ in minimum specific fuel consumption mode: (a) BAS, (b) GA and (c) PSO.

Figure 8. The decrease of $T_4$ in minimum turbine inlet temperature mode: (a) BAS, (b) GA and (c) PSO.
envelop, the decrease of $S_\ell$ is more than 4% and the decrease of $T_4$ is more than 20k.

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