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Control allocation for aircraft with input constraints based on improved cuckoo search algorithm

Yao LU [a,*], Chao-yang DONG [a], Qing WANG [b]

[a] School of Aeronautic Science and Engineering, BUAA, Beijing 100191, China
[b] School of Automation Science and Electrical Engineering, BUAA, Beijing 100191, China

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ABSTRACT

The control allocation problem of aircraft whose control inputs contain integer constraints is investigated. The control allocation problem is described as an integer programming problem and solved by the cuckoo search algorithm. In order to enhance the search capability of the cuckoo search algorithm, the adaptive detection probability and amplification factor are designed. Finally, the control allocation method based on the proposed improved cuckoo search algorithm is applied to the tracking control problem of the innovative control effector aircraft. The comparative simulation results demonstrate the superiority and effectiveness of the proposed improved cuckoo search algorithm in control allocation of aircraft.

1. Introduction

As the development of the aircraft technology, for superior maneuver and reliability, more and more advanced aircraft, even unmanned aerial vehicles and missiles, deploy multiple and redundant effectors on their bodies. Therefore, an appropriate control allocation method is necessary for the control systems of these aircraft to use their effectors efficiently. Control allocation is a hot issue in the field of flight control. Many methods have been proposed for solving various control allocation problems [1]. Most of the time, the control allocation problem can be represented as an optimization problem. Therefore, the designed control allocation methods are usually based on some optimization methods.

For an aircraft, its control allocation problem is apparently related to its effectors. Sometimes some unconventional effectors will make the control allocation problem different from the conventional problems and difficult to be solved. A characteristic example is the innovative control effector (ICE) aircraft which is introduced by Lockheed Martin Tactical Aircraft Systems [2]. This aircraft uses several distributed arrays each of which contains lots of actuators as effectors. The particularity is that each actuator can only provide either full or no control energy [3]. We can group those actuators which have almost the same full control energies together and then the control allocation problem of the ICE aircraft can be translated into an integer programming problem with some constraints. Actually, the integer constraints are present in many aircraft effectors, such as the reaction control system (RCS) and so on.

Different from the normal linear programming or quadratic programming problem, most of the integer programming problems are non-deterministic polynomial hard (NP-hard) problems and their optimum solutions are usually hard to be obtained. Some classical methods, such as the branch-bound method and cutting plane method, are usually used to solve the integer linear programming problem and they are effective when the scale of the problem is small. However, with the increase of the scale of the problem, the computational complexities of the classical methods will increase rapidly and cannot meet the practical requirements. Therefore, the metaheuristic algorithms have attracted more and more attentions. There have been recently many studies using metaheuristic algorithms to solve aircraft control allocation problems [4–7]. The cuckoo search algorithm (CSA) is a relatively novel and promising metaheuristic algorithm proposed by Yang and Deb [8]. Some studies have demonstrated that its search capability is better than many other metaheuristic algorithms [9,10]. Therefore, the CSA has been applied to many application domains, such as

* Corresponding author.
E-mail address: luyaosacred@126.com (Y. LU).
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parallel machine scheduling [11], total cost of ownership for supplier selection problem [12], maximum power point tracking for Photovoltaic System [13] and structural damage identification [14]. However, the efficiency of the basic CSA is still unsatisfactory. Therefore, the algorithm need be improved when it is used.

In this paper, an improved CSA is proposed for solving the aircraft control allocation problem with integer constraints. The remaining sections of this paper are organized as follows. Section 2 describes the aircraft control allocation problem with integer constraints. Section 3 formulates the design of the control allocation method based on an improved CSA. The simulation results established upon the proposed method and some compared methods are given in Section 4. Finally, some concluding remarks are summarized in Section 5.

2. Problem formulation

2.1. Description of the aircraft model

Consider the linearized dynamic model of aircraft

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{A}\boldsymbol{x}(t) + \boldsymbol{B}_v\boldsymbol{v}(t) \tag{1}$$

where $\boldsymbol{x}\in\mathrm{R}^{c_1}$ represents the states and $\boldsymbol{v}\in\mathrm{R}^{c_2}$ represents the virtual control input. The control objective is to track a reference model

$$\dot{\boldsymbol{x}}_{\mathrm{m}}(t) = \boldsymbol{A}_{\mathrm{m}}\boldsymbol{x}_{\mathrm{m}}(t) + \boldsymbol{B}_{\mathrm{m}}r(t) \tag{2}$$

where $r(t)$ is the reference input. Assume that the system (A, B_v) is known and controllable, then the virtual control law can be designed as

$$\boldsymbol{v}(t) = -\boldsymbol{K}_1\boldsymbol{x}(t) + \boldsymbol{K}_2 r(t) \tag{3}$$

where $\boldsymbol{K}_1, \boldsymbol{K}_2$ are the gain matrices which meet the following matched conditions

$$\begin{cases} \boldsymbol{A} - \boldsymbol{B}_v\boldsymbol{K}_1 = \boldsymbol{A}_{\mathrm{m}} \\ \boldsymbol{B}_v\boldsymbol{K}_2 = \boldsymbol{B}_{\mathrm{m}} \end{cases} \tag{4}$$

Let $\boldsymbol{e}$ represent the tracking error. Under the virtual control law (3) the tracking error dynamical system can be described by

$$\dot{\boldsymbol{e}}(t) = \dot{\boldsymbol{x}}(t) - \dot{\boldsymbol{x}}_{\mathrm{m}}(t) = \boldsymbol{A}_{\mathrm{m}}\boldsymbol{e}(t) \tag{5}$$

The system (5) shows that the tracking error $\boldsymbol{e}$ is asymptotically stable provided $\boldsymbol{A}_{\mathrm{m}}$ is a Hurwitz matrix.

2.2. Control allocation problem

After obtaining the virtual control input $\boldsymbol{v}$, the control system on the aircraft need deploy the effectors to achieve it. Let $\boldsymbol{n} = [n_1, \ldots, n_{c_3}]^{\mathrm{T}}$ represent the actual control command from the effectors. Assume that $n_i, i = 1, 2, \ldots, c_3$ is restricted to the following compact set Ω_i

$$\Omega_i = \{n_i | \underline{n}_i \le n_i \le \overline{n}_i, n_i \in Z\} \tag{6}$$

and the effector model is a linear model in the form

$$\boldsymbol{v} = \boldsymbol{B}_u\boldsymbol{n}, n_i \in \Omega_i \tag{7}$$

The objective of control allocation is to find out a suitable actual control command $\boldsymbol{n}$ to achieve the virtual control input $\boldsymbol{v}$. Then the problem can be converted into an integer programming problem and the fitness function is defined as

$$J(\boldsymbol{n}) = \|\boldsymbol{C}(\boldsymbol{v} - \boldsymbol{B}_u\boldsymbol{n})\|_2, \quad n_i \in \Omega_i \tag{8}$$

where $\boldsymbol{C}$ is a definite weighting matrix, $\|\cdot\|_2$ is 2-norm.

It should be noticed that we cannot obtain the actual control command by rounding $\boldsymbol{n} = \boldsymbol{B}_u^{+}\boldsymbol{v}$ where $(\cdot)^{+}$ represents pseudo-inverse because the solution is inexact. Next, we propose an improved CSA for the design of the control allocation method.

3. Design of control allocation method

3.1. Basic cuckoo search algorithm

The CSA combines the cuckoo breeding behavior with a random walk called Lévy flight. Some studies have demonstrated that Lévy flight is an optimized search pattern for non-replenishable targets at unknown positions [15,16]. The CSA is established based on the following three idealized rules [8]:

1) Each cuckoo lays only one egg once and places it in a random nest.
2) The best nest including the high quality egg will be carried over to the next generation.
3) The egg can be discovered by the nest owner with a detection probability $p_a \in [0, 1]$. When one egg is discovered, the nest owner will abandon the nest and build a new one in somewhere.

Controlled by the detection probability p_a and a random number θ drawn from a uniform distribution $\theta \sim U(0, 1)$, the CSA uses a combination of local random walk and global explorative random walk to search the optimum solution. Let $\boldsymbol{\tau}_j^g$ represent the j-th cuckoo in the population of g-th generation. When generating a new solution $\boldsymbol{\tau}_j^{g+1}$, if $p_a \ge \theta$, the global random walk is performed via Lévy flights

$$\boldsymbol{\tau}_j^{g+1} = \boldsymbol{\tau}_j^g + \boldsymbol{\alpha} \otimes \boldsymbol{L}(\lambda) \tag{9}$$

where $\alpha > 0$ is the amplification factor, $\otimes$ denotes Hadamard multiplication, $\boldsymbol{L}(\lambda) = [l_1(\lambda), \cdots, l_{c_3}(\lambda)]^{\mathrm{T}}$ is the random step path and $l_i(\lambda)$ follows the Lévy distribution

$$l_i(\lambda) \sim g^{-\lambda}, \quad (1 < \lambda \le 3) \tag{10}$$

where λ is a Lévy flight parameter, $l_i(\lambda)$ can be obtained by

$$l_i(\lambda) = \frac{\mu}{|\nu|^{1/\beta}} \tag{11}$$

where $\beta = \lambda - 1$, μ and ν are drawn from normal distributions

$$\mu \sim N\left(0, \sigma_\mu^2\right), \quad \nu \sim N\left(0, \sigma_\nu^2\right) \tag{12}$$

where σ_μ, σ_ν represent the standard deviations of the corresponding normal distributions and the values are

$$\sigma_\mu = \left\{\frac{\Gamma(1+\beta)\sin(\pi\beta/2)}{\Gamma[(1+\beta)/2]\beta 2^{(\beta-1)/2}}\right\}^{1/\beta}, \quad \sigma_\nu = 1 \tag{13}$$

where Γ is the standard Gamma function.

If $p_a < \theta$, the new solution is produced by local random walk which can be written as