Improved Shuffled Frog Leaping Algorithm Optimizing Integral Separated PID Control for Unmanned Hypersonic Vehicle

Liang Bingbing（梁冰冰），*Jiang Ju*（江驹），*Zhen Ziyang*（甄子洋）*，*Ma Kun*（马坤）

College of Automation Engineering，Nanjing University of Aeronautics and Astronautics，Nanjing 210016，P. R. China

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Abstract：To solve the flight control problem for unmanned hypersonic vehicles，a novel intelligent optimized control method is proposed. A flight control system based on integral separated proportional-integral-derivative (PID) control is designed for hypersonic vehicle，and an improved shuffled frog leaping algorithm is presented to optimize the control parameters. A nonlinear model of hypersonic vehicle is established to examine the dynamic characteristics achieved by the flight control system. Simulation results demonstrate that the proposed optimized controller can effectively achieve better flight control performance than the traditional controller.

Key words：hypersonic vehicles；flight control；shuffled frog leaping algorithm；unmanned aerial vehicles（UAVs）

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0 Introduction

Hypersonic vehicles are designed to operate over a range of flight conditions from low subsonic speeds to flight at high Mach numbers in the uppermost part of the earth's atmosphere. The research of air-breathing hypersonic vehicles poses unique challenges. Control techniques are one of the key technologies for these classes of aircrafts. Several control strategies have been proposed for the hypersonic flight vehicles. A robust tracking controller was designed，which achieved global exponential tracking control of a model reference system where the plant dynamics contained varying parametric uncertainties[1]. A controller was designed for rotation motion dynamics of a hypersonic vehicle，which contained inner-fast/outer-fast loops nonlinear predictive controllers[2]. A tracking controller for an air-breathing hypersonic vehicle was proposed which used the aero-propulsive and the elevator-to-lift coupling to design controllers[3]. However，these methods are a little complex to be realized. Proportional-integral-derivative（PID）control is still the most applicable engineering method for flight vehicles[4].

Swarm intelligence（SI）is the collective intelligent behavior of decentralized，self-organized systems. Inspired from natural systems，several artificial SI algorithms are presented，including particle swarm optimization，ant colony optimization，artificial bee colony algorithm，differential evolution，artificial immune systems，which have been widely applied to robotics and other engineering fields. Shuffled frog leaping algorithm（SFLA），originally proposed by Eusuff and Lansey[5-7] is another meta-heuristic SI algorithms inspired by biotic community. There are two analogies for this algorithm. One is the frogs swarm leaping on the stones to search for food by improving its memes. The other is a culture population such as an earlier culture which develops an idea such as pottery. Recently，SFLA has been widely used in engineering，for instance，parameter identification[8]，control of selective and total harmonic distortion[9]，fuel management[10]，loss reduction and power generation of distributed generators[11]. Meanwhile，there have been several kinds of modifications for SFLA. To further improve the local searching ability of SFLA，a power law external optimization neighborhood searching strategy can be adopted[12]. Zhen，et al. presented a memetic algorithm[13] and an improved

* **Corresponding author**：Zhen Ziyang，Associate Professor，E-mail：zhenziyang@nuaa.edu.cn.

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SFLA[14].

Authors apply a controller design methodology here to an unmanned air-breathing hypersonic vehicle, which uses an integral separated PID controller to track velocity and pitch angle reference commands. Moreover, an improved SFLA (ISFLA) is presented to intelligently optimize the controller parameters which are difficult to be determined.

The modeling and control problem of unmanned hypersonic vehicle can be described by the following equations, defining a non-linear longitudinal model of the unmanned hypersonic vehicle

$$\dot{V}=\frac{T\cos\alpha-D}{m}-g\times\sin\gamma \tag{1}$$

$$\dot{\gamma}=\frac{L+T\sin\alpha}{mV}-\frac{g\times\cos\gamma}{V} \tag{2}$$

$$\dot{h}=V\sin\gamma \tag{3}$$

$$\dot{\alpha}=q-\dot{\gamma} \tag{4}$$

$$\dot{q}=M_{yy}/I_{yy} \tag{5}$$

where m denotes the vehicle mass, $V\in\mathbf{R}$ the forward velocity, $h\in\mathbf{R}$ the altitude, $\alpha\in\mathbf{R}$ the angle of attack, $\theta\in\mathbf{R}$ the pitch angle, $q\in\mathbf{R}$ the pitch rate, $T\in\mathbf{R}$ the thrust, $D\in\mathbf{R}$ the drag, $L\in\mathbf{R}$ the lift, $M\in\mathbf{R}$ the pitching moment about the body y-axis, and I_{yy} the moment of inertia.

And

$$L=0.5\rho V^2 sC_L \tag{6}$$

$$D=0.5\rho V^2 sC_D \tag{7}$$

$$T=0.5\rho V^2 sC_T \tag{8}$$

$$M_{yy}=0.5\rho V^2 sc[C_M(\alpha)+C_M(\delta_e)+C_M(q)] \tag{9}$$

where δ_e is the elevator deflection, and C_T the thrust coefficient

$$C_T=\begin{cases}\kappa_1\beta & \text{if}\quad \beta>1\\ \kappa_2+\kappa_3\beta & \text{if}\quad \beta<1\end{cases} \tag{10}$$

Dynamic model of the engine is expressed by a second-order differential equation

$$\ddot{\beta}=-2\xi\omega\dot{\beta}-\omega^2\beta+\omega^2\beta_c \tag{11}$$

where β is the engine throttle regulator variable, and β_c the throttle angle.

Flight control for unmanned hypersonic vehicles requires a high degree of precision, and even greater than that for a conventional aircraft in most cases.

1 Basic Shuffled Frog Leaping Algorithm and Its Improvement

In SFLA, there is a population of frogs representing a set of possible solutions. The frog group is divided into several subsets referred to as memplexes, and each memeplex acts as an independent culture. Afterwards, the selection strategy of a submemplex in each memplex that the greater coefficients are considered for the frogs with better fitness functions is adopted. And then, local search starts from the worst frog to leap to the best frog in any memplex. After several generations of each memplex, ideas are passed between memeplexes in a shuffling process. The local search and the shuffling process continue until the solution criterion is satisfied.

1.1 Memeplexes partition

A population $X=\{x_i, f_i, i=1,\cdots,F\}$ of frogs is initialized with position within the searching domain and sorted in a descending order according to their fitness values where x_i denotes the i-th frog's position, and f_i its fitness. The position of the frog with the best fitness is represented as x_X. Partition the population into m memeplexes $\{Y_1, Y_2, \cdots, Y_m\}$. Each contains n frogs, and

$$Y_i=[(x_j, f_j)\mid x_j=x_{i+m(j-1)}, f_j=f_{i+m(j-1)},\ j=1,\cdots,n] \tag{12}$$

1.2 Memeplexes evolution

Step 1 Since the frogs tend to concentrate around the best frog that may be a local optimum, some members in any memeplex are considered as a submemeplex (including q frogs) to avoid convergence to the local optimum. The weights are assigned with a triangular probability distribution.

$$p_i=\frac{2(n+1-i)}{n(n+1)},\quad i=1,\cdots,n \tag{13}$$

The frogs with higher fitness have bigger weights and will be selected in the submemeplex.

Step 2 The worst frog in submemeplex leaps towards the best frog in the memplex, and the new position is thus obtained by a leaping step.

$$d^{k+1}=\begin{cases}\min\{\mathrm{Int}[r^k(x_{\mathrm{B}}^k-x_{\mathrm{W}}^k)], d_{\max}\}\\ \qquad \text{if}\quad x_{\mathrm{B}}^k\geqslant x_{\mathrm{W}}^k\\ \min\{\mathrm{Int}[r^k(x_{\mathrm{B}}^k-x_{\mathrm{W}}^k)], -d_{\max}\}\\ \qquad \text{if}\quad x_{\mathrm{B}}^k< x_{\mathrm{W}}^k\end{cases} \tag{14}$$

where x_{B}, x_{W} denotes the best and the worst positions of the submemeplex, respectively, Int(•) the rounding function, $d_{\max}$ the maximum step size allowed, r a random number, and k a generation number. If the new position of the worst frog is better than before, the position of the worst frog is updated by

$$x_q^{k+1} = x_q^k + d^{k+1} \tag{15}$$

Otherwise, the worst frog leaps towards the global best frog, then in Eq. (14) x_B is replaced by x_X. If the worst frog also cannot find a better solution, a random position is generated for the worst frog.

Step 3 Subsequently, the frogs are sorted in a descending order according to their fitness. Repeat Steps 1—3 and evolve the submemeplexes with G_1 generations.

1.3 Shuffle of memeplexes

After completed local search in each memeplex, all of memeplexs are shuffled, and the frogs are reorganized in a descending order of fitness. The population is repeatly divided into memeplexs, followed by the local search process, until memetic evolution generation G_2 is obtained.

1.4 Improvement of SFLA

The improved SFLA (ISFLA) is presented in three segments as follows:

(1) When the SFLA is to solve continuous optimization problems, the leaping step needs to be modified into a continuous form. Hence the "Int" function should be canceled. Moreover, boundary limitation for the leaping step should also be canceled, and the substitute is the boundary limitation of frog position, in order to guarantee it in the feasible searching space.

(2) The partition strategy in the standard SFLA is replaced by a random strategy, which is realized by the following method: generating a random number sequence, whose length is the size of the frogs swarm; sorting these random numbers, then the order sequence is obtained; selecting in turn a number of frogs in this order sequence to form a memeplex.

(3) The evolution of submemeplexes in SFLA is the process of the worst frog to adjust its position, which is insufficient learning for the population, especially for the better frogs with fewer learning chances. Therefore, the submemeplexes is canceled and accordingly all the frogs in memeplexes can take part in the evolution. Furthermore, the learning object in standard SFLA is the best frog in submemeplex or in swarm. This singularity may cause the algorithm to fall into the local optimum. Therefore, in ISFLA frogs can learn from any frog with a better performance.

According to the above modification, the leaping step of the i-th frog is modified as

$$d_i^{k+1} = r^k (x_r^k - x_i^k) \quad i = 1, 2, \cdots, n \tag{16}$$

where x_r^k is a randomly selected frog with the better performance than x_i^k. This strategy is beneficial to avoid the local optimum and thus improve the performance of entire group. And then the new position of the i-th frog is

$$x_i^{k+1} = \begin{cases} \min\{x_i^k + d_i^{k+1},\ b\} \\ \max\{x_i^k + d_i^{k+1},\ a\} \end{cases} \tag{17}$$

The evolution of memeplexes is essenceially the process of mutual learning among the group. So the performance of the whole frog group is enhanced after the internal evolution and the gap between the best frog and the worst frog are decreased.

The implementation flow of the ISFLA is shown in Fig. 1.

2 Flight Control Laws for Unmanned Hypersonic Vehicle

The flight control system of unmanned hypersonic vehicle is composed of two control loops. One is the pitch angle loop, and the other the velocity loop. The control laws of these two loops are designed based on the integral separated PID control strategy, expressed by

$$\delta_e = \begin{cases} k_{p,\theta}(\theta_d - \theta) + k_{i,\theta}\int(\theta_d - \theta)\mathrm{d}t + k_{d,\theta}\dfrac{\mathrm{d}(\theta_d - \theta)}{\mathrm{d}t} & |\theta_d - \theta| < e_\theta \\ k_{p,\theta}(\theta_d - \theta) + k_{d,\theta}\dfrac{\mathrm{d}(\theta_d - \theta)}{\mathrm{d}t} & |\theta_d - \theta| \geqslant e_\theta \end{cases} \tag{18}$$

$$\beta_c = \begin{cases} k_{p,V}(V_d - V) + k_{i,V}\int (V_d - V)\,dt + k_{d,V}\dfrac{d(V_d - V)}{dt} & |V_d - V| < e_V \\ k_{p,V}(V_d - V) + k_{d,V}\dfrac{d(V_d - V)}{dt} & |V_d - V| \geq e_V \end{cases} \tag{19}$$

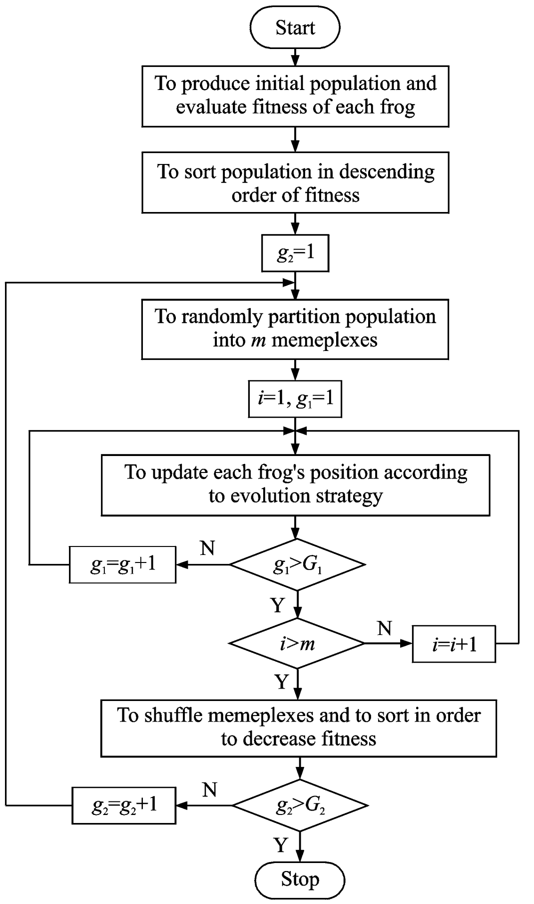

Fig. 1 Flowchart of ISFLA

It should be mentioned that the parameters vector $\boldsymbol{K}=[k_{p,\theta}, k_{i,\theta}, k_{d,\theta}, k_{p,V}, k_{i,V}, k_{d,V}]$ should be determined in advance. Generally, the transfer functions are established and the root locus technique is adopted to design the control parameters. However, it is complex thus being hard to find optimal or near optimal parameters.

Therefore, ISFLA is used to optimize the parameter vector $\boldsymbol{K}$. The flowchart of ISFLA describing the optimization process is shown in Fig. 1.

3 Simulation and Analysis

To study the control performance of velocity and pitch attitude of an unmanned hypersonic vehicle in climbing flight, the vehicle is trimmed in level flight at 3 500 m/s and altitude of 30 500 m, as an initial flight state. The hypersonic vehicle is desired to track the velocity and pitch attitude references initialized at 3 200 m/s, 5°, respectively.

For the proposed ISFLA, the population size is set as 50, and the number of the memeplexes is 5 and 10 within each memeplex. Three memetic iterations in each memeplex and eight shuffling process in population are performed. The proposed ISFLA optimized integral separated PID controller is compared with the traditional integral separated PID controller. For the sake of fairness, a set of parameters in the traditional integral separated PID controller is considered as initial candidate parameters in ISFLA.

Figs. 2, 3 show the velocity and pitch angle responses by the manipulation of elevator and throttle, under the integral separated PID controller and ISFLA optimized integral separated PID controller, respectively.

The above simulation results show that the proposed ISFLA optimized integral separated PID controller is characterized by a faster dynamic re-

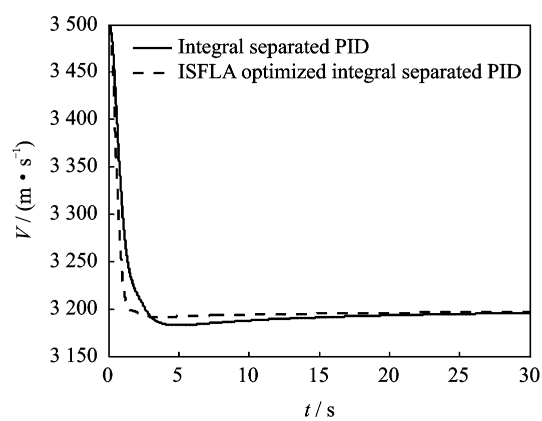

Fig. 2 Velocity response

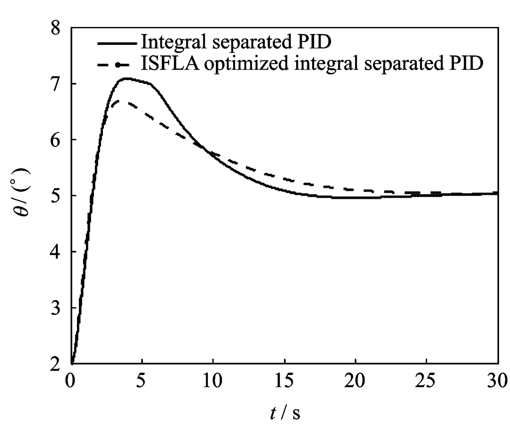

Fig. 3 Pitch attitude response

sponse, a remarkably smaller error during the entire maneuver, and a higher steady error. Obviously, the improvement of control responses is benefit from the optimized controller parameters obtained by ISFLA.

4 Conclusions

A nonlinear and physics-based model of the longitudinal dynamic model for an unmanned hypersonic vehicle is established. An integral separated PID control based flight control system of the hypersonic vehicle is designed for longitudinal maneuver control. The basic SFLA is modified into a continuous form, therefore it can be used in the control parameter optimization problem, and the learning strategy is improved in terms of simplicity and fast convergence. And then, the ISFLA is applied in control parameter optimization for obtaining a near optimal control gains. The simulation results demonstrate that the flight control system can achieve excellent pitch attitude angle and velocity tracking performance. Parameter optimization problem of the whole flight control system of the unmanned hypersonic vehicle is hoped to be solved in future work.

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