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Chaotic Artificial Bee Colony Optimization Approach to Aircraft Automatic Landing System

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Abstract: This paper presents an aircraft Automatic Landing System (ALS) that uses Chaotic Artificial Bee Colony (CABC) optimization. Analysis of aircraft landing process and wind disturbance are provided. The couple behavior between the thrust and the elevator during automatic landing is also investigated. A vertical rate referenced guidance system and an angle of attack referenced Approach Power Compensation System (APCS) are developed and evaluated for use in automatic landing. CABC optimization techniques are applied to calculate a set of optimal filter parameters and control gains for the entire closed-loop control system. A series of comparative experimental results verified the feasibility and effectiveness of our proposed approach.

Keywords: Automatic Landing System (ALS), Approach Power Compensation System (APCS), Wind disturbance, Chaotic Artificial Bee Colony (CABC), Optimization.

1. INTRODUCTION

The landing of an aircraft is the most difficult operation in regard to safety issues. Automatic landing of an aircraft has been a problem since the early stages of their development. A large source of touchdown error is the turbulent air environment found in the approach path and the ground effect also reduces the landing accuracy. In order to overcome these difficulties and expand the operational envelope of the aircrafts, there has been a lot of research and development in the area of auto landing. The robust and sliding mode control theory has been used to solve linear and nonlinear autoland control problems and it is well known for its invariance of quasi-sliding mode which manifest ideal robustness. The H_2/H_∞ technique is also used to eliminate the influence of uncertainties and disturbances (Li et al., 2004a).

The objective of the controller design is to provide precise automatic control of the approach and landing of an aircraft in the longitudinal axis. Most of the improvements in the Automatic Landing System (ALS) system have been on the guidance instruments. However, very few literatures focus on the design of a complete ALS which consists of an autopilot and an Approach Power Compensation System (APCS). An ALS provides flight approach control until touchdown and it should be designed to couple many commands to the aircraft autopilot and together with an APCS provide automatic flight and thrust control. Recently, some researchers have applied some intelligent computation methods such as neural networks (Juang and Cheng, 2006), fuzzy systems (Oosterom and Babuška, 2006), particle swarm optimization (Li et al., 2004b), GAs, and hybrid systems to flight control to increase the flight controller's adaptively to different environments (Duan et al., 2013a). Specifically, the bio-inspired methodologies offer a simple and effective way to design feedback controllers (Kim et al., 2013, Duan et al., 2013b).

Artificial Bee Colony (ABC) algorithm was originally presented by Dervis Karaboga in 2007, based on the intelligent collective behaviour of honey bees on searching food source. Compared with the other bio-inspired computation methods, the prominent advantage of ABC algorithm is that it combines global search and local search in each iteration. The ABC algorithm has been widely used in path planning, multi-formation reconfiguration and multi-vehicle coordinate problems.

The Chaotic Artificial Bee Colony (CABC) algorithm is based on the model of basic ABC, and a chaotic mechanism is adopted for preventing the basic ABC falling into local optimum as well as finding the optimal parameters. Chaos is a kind of characteristic of non-linear systems and it is a new optimization mechanism due to its special ability to avoid being trapped in local optimum.

In this paper, the automatic landing system design is modelled as a parameter optimization problem with dynamical and algebraic constraints. For this reason, artificial intelligence algorithms and/or other optimization methods can be utilized to find the optimal solution. The ability of function optimization makes CABC effective for adjusting controller gains. The robustness of the controller is obtained by choosing optimal control gains that allow a wide range of disturbances to the controller in this study.

The remainder of this paper is organized as follows. The next section introduces the automatic landing problem and the mathematic model of the aircraft is described. Section 3 gives a description of the main architecture of automatic landing system. The basic ABC and our CABC algorithm are presented in Section 4, and the proposed CABC method is applied to automatic landing system design in Section 5. The comparative experimental results are given in Section 6, followed by our concluding remarks in Section 7.

2. AIRCRAFT AUTOMATIC LANDING ANALYSIS

2.1 Landing Process and Wind Turbulence

The reference trajectory of a normal landing process is shown in Fig. 1. It consists of two parts: glide path and flare path. When the aircraft reaches the glide slope marker, the glide path signal is intercepted. As the aircraft descends along the glide path its altitude H and vertical rate $\dot{H}$ must be controlled, which means the pitch, attitude and speed of the aircraft should be held constant.

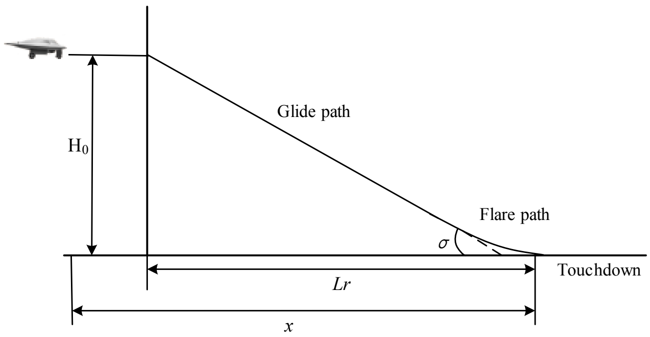

Fig. 1. The reference landing trajectory.

The glide slope capture can be formulated as:

$$\begin{aligned} H &= H_0 + (x - Lr)\tan\sigma \\ \dot{H} &= -V_0 \sin\sigma \end{aligned} \tag{1}$$

where x, Lr and σ are shown in figure 1, and σ is 2.5° or 3.0°.

A flare maneuverer is executed as the aircraft descends to about 20 meters, which allows a soft touchdown on the runway surface. A flare maneuverer means reducing the vertical rate of descent along with the reduction of altitude, which can be formulated as:

$$\dot{H}(t) = -\frac{1}{\tau} H(t) \tag{2}$$

Wind turbulence is an important factor to the precision requirement for the automatic landing. The formation of wind turbulence is the process by a kind of randomness changes. Wind shear type turbulence is mostly used for aircraft landing studies, which can be expressed as:

$$w(H) = w_{20} \frac{\ln(H / z_0)}{\ln(20 / z_0)} \tag{3}$$

where H represents the aircraft altitude, z_0 and w_{20} are the reference wind velocities.

2.2 Description of Longitudinal Aircraft Movement

The nondimensional aerodynamic coefficients can be divided into longitudinal and lateral modes, with longitudinal modes being forward force, downward force, and pitching moment, and lateral modes being sideways force, roll moment, and yaw moment. Longitudinal coefficients are primarily dependent on longitudinal states and elevator inputs (Zheng et al., 2013).

During a landing process, the aircraft can be modelled as linear time invariant state-space perturbation models, with the nominal trajectory being steady, level trimmed flight. The linear longitudinal motion equation of aircraft in non-uniform atmosphere is given as follows (Liang et al., 2012):

$$\begin{bmatrix} \Delta\dot{u} \\ \Delta\dot{w} \\ \Delta\dot{\theta} \\ \Delta\dot{q} \end{bmatrix} = \begin{bmatrix} X_u & X_w & -g & 0 \\ Z_u & Z_w & 0 & U_0 \\ 0 & 0 & 0 & 1 \\ M_u & M_w & 0 & M_q \end{bmatrix} \begin{bmatrix} \Delta u \\ \Delta w \\ \Delta\theta \\ \Delta q \end{bmatrix} + \begin{bmatrix} X_{\delta_T} & X_{\delta_e} \\ Z_{\delta_T} & Z_{\delta_e} \\ 0 & 0 \\ M_{\delta_T} & M_{\delta_e} \end{bmatrix} \begin{bmatrix} \Delta\delta_T \\ \Delta\delta_e \end{bmatrix} + \begin{bmatrix} -X_u & -X_w & 0 \\ -Z_u & -Z_w & 0 \\ 0 & 0 & 0 \\ -M_u & -M_w & -M_q \end{bmatrix} \begin{bmatrix} u_g \\ w_g \\ q_g \end{bmatrix} \tag{4}$$

$$\dot{H} = -w + V_0\theta \tag{5}$$

where Δu is the aircraft longitudinal velocity and Δw is the aircraft vertical velocity.

As $\Delta w = V_0 \Delta\alpha$, we can get an equation as follows:

$$\dot{x} = Ax + Bu + \Gamma\omega \tag{6}$$

where $x = [\Delta v \quad \Delta\alpha \quad \Delta\theta \quad \Delta q]^T$, $u = [\Delta\delta_T \quad \Delta\delta_e]^T$ and $\omega = \begin{bmatrix} u_g & w_g & q_g \end{bmatrix}^T$, Δv is the aircraft velocity, $\Delta\alpha$ is the angle of attack, $\Delta\theta$ is the pitch angle, Δq is the pitch rate, $\Delta\delta_T$ is the throttle setting, $\Delta\delta_e$ is the incremental elevator angle, ω is the airflow disturbance.

3. AUTOMATIC LANDING SYSTEM DESIGN

3.1 Vertical Rate Referenced Autopilot

The basic frame diagram of an automatic landing system in the longitudinal axis of the airplane is shown in Fig. 2. In this system the radar measures the actual altitude of the aircraft to land continuously (Akmeliawati and Mareels, 2010). The height error, the difference between the desired and actual descending trajectories, is transformed into attitude angle (pitch angle and angle of attack) commands by a guidance system (Herissé et al., 2012). The autopilot and approach power compensation system use these attitude angle commands to control the flight-path angle of the aircraft to eliminate the altitude error.

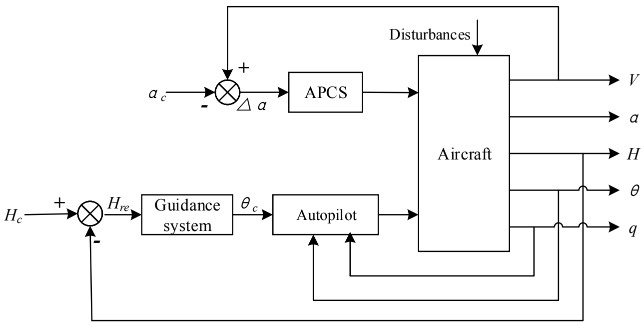

Fig. 2. Main architecture of a longitudinal automatic landing system.

The pitch attitude is controlled by aircraft pitch autopilot as shown in Fig. 3, the pitch command θ_c is generated from a vertical rate referenced guidance system (Kim and Kim, 2013). A simplified structure of a vertical rate referenced guidance system, which is a PID-type guidance system, is shown in Fig. 4. Its inputs consist of altitude and altitude rate commands along with aircraft altitude and altitude rate.

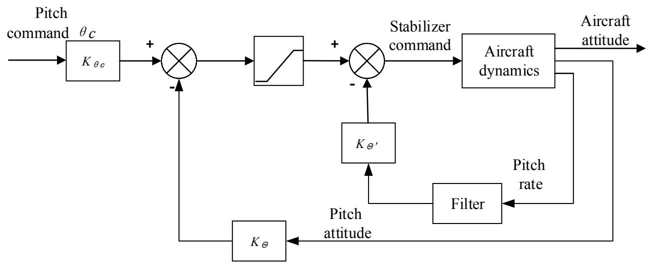

Fig. 3. The pitch command autopilot.

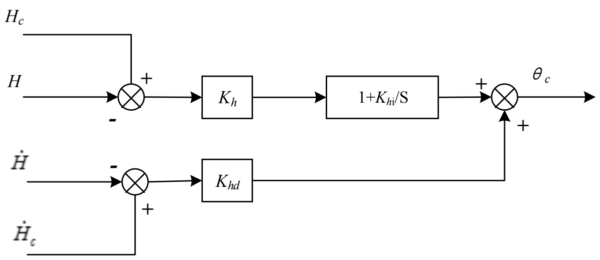

Fig. 4. Vertical rate referenced guidance system.

The longitudinal autopilot shown in Fig. 3 is used to make the pitch angle θ can follow the expected pitch angle θ_c . Based on the feedback and correction technology, the order of the flight control system can be reduced with reasonable configuration of zeros and poles and the expected response characteristics can be realized. The vertical rate referenced guidance system is used to generate expected pitch command based on the vertical rate $\dot{H}$. In the design of this guidance system, there are 3 parameters K_h, K_{hd}, and K_{hi} that need to be adjusted, which can be considered as an altitude referenced PID controller.

3.2 Design of APCS with Constant Angle of Attack

The autopilot achieves the commanded pitch angle, but it is the flight-path angle that must be controlled to land the aircraft using the automatic landing system. This can be accomplished by using the approach power compensation system. The commonly used approach power compensation system includes the system with constant speed and the system with constant angle of attack. Previous researches have already demonstrated that the path angle can track the pitch angle quickly and accurately under the control of the approach power compensation system with constant angle of attack. So we design an approach power compensation system with constant angle of attack in this paper.

The angle of attack referenced control law design includes the following input terms: angle of attack for the primary feedback, integral angle of attack to eliminate biases and to insure that the angle of attack will return to the commanded reference value, normal acceleration to augment the flight path damping, elevator/stabilizer position and pitch rate to provide a lead term for aircraft pitch maneuvers. The block diagram of the approach power compensation system is shown in Fig. 5.

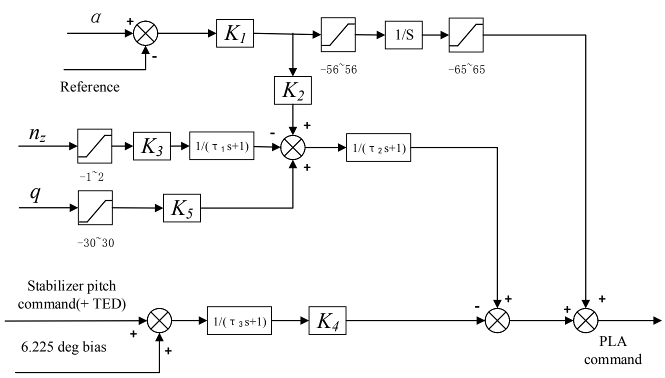

Fig. 5. Architecture of the approach power compensation system.

The control law design is optimizing the approach power compensation system control gains terms to minimize flight path deviations in turbulence. In the design of this system, there are 5 parameters K_1, K_2, K_3, K_4 and K_5 that need to be determined, which corresponding to angle of attack control gains and other damping coefficients.

4. PRINCIPLES OF THE CHAOTIC ABC ALGORITHM

ABC algorithm is one of the most recently proposed algorithms by Karlvon Frisch, based on the collective behaviour of honey bees (Duan et al., 2010b). In optimization problem, the position of a food source represents a possible solution, and the nectar amount of a food source corresponds to the fitness function value of the solution. (Karaboga, 2009).

Chaos is a highly unstable motion of deterministic systems in finite phase space which often exists in nonlinear systems

(Lorenz, 1963). Chaos theory has been applied to a number of fields, and the ergodicity and irregularity of the chaotic variable can be used to help the algorithm to jump out of the local optimum. Consider the well-known logistic equation:

$$x_{k+1} = \frac{a}{4}\sin(\pi x_k) \tag{7}$$

where 0<a≤4, a quite small difference in the initial value of x would induce a big difference in the long-time response. The process of the chaotic position update formula can be defined through the Eq. (7). The main difference between ABC and CABC is that CABC produces new solutions for the employed bees by using Eq. (7) (Duan et al., 2010c).

5. CABC FOR TUNING CONTROL PARAMETERS

The control gains tuning of the vertical rate referenced guidance system and the approach power compensation system can be treated as the typical continual spatial optimization problem. CABC is a novel way for solving the problem. CABC can be applied to adjust system control gains to reduce the workload of conventional designer. Once the bounds of the control gains are set, CABC will search the corresponding space automatically to find the optimal parameters. The process in conventional design is conducted manually, now it can be done automatically. Bio-inspired computation can be applied to promote the automation of controller design (Luo and Duan, 2013).

For utilizing the proposed CABC algorithm to obtain the optimal parameters combination for the automatic landing system, the fitness function is given as follows:

$$J = \int_0^{T_t} t\left|\varepsilon(t)\right| dt \tag{8}$$

where $\varepsilon(t) = w_1(\alpha(t) - \alpha_c) + w_2(\dot{H}(t) - \dot{H}_c)$ is the error between aircraft outputs and referenced signals. The smaller J is, the better the solution is. The position vector of the solution in CABC is defined by:

$$x = [K_h, K_{hd}, K_{hi}, K_1, K_2, K_3, K_4, K_5] \tag{9}$$

The vector x represents the 8 parameters (3 in longitudinal guidance system and 5 in approach power compensation system) that need to be tuned, and all the parameters have the constrain of ± 20, which is set according to exact experience.

The process of CABC algorithm for solving automatic landing system parameters tuning can be described as:

Step 1: Initialize the parameters of CABC optimization algorithm, such as the population of the bee colony *Ns*, the number of employed bees *Ne* and the number of the unemployed bees *Nu*:

$$N_s = N_e + N_u \tag{10}$$

In general, define *Ne* = *Nu*, and set *Ns*=2500. Denote the largest searching times *Limit*=5.

Step 2: The algorithm randomly generates sets of x.

Step 3: According to the parameters of the employed bees, calculate the cost of each automatic landing process confirmed by each solution in SIMULINK based on Eq. (8).

Step 4: For the ith employed bee, first engender an integer j randomly between 1 and D and a random integer k between 1 and *Ne*, and then the jth parameter of the ith employed bee could be updated by (11).

$$y_i''(j) = y_i'(j) + \frac{a}{4}\sin(\pi(y_i'(j) - y_k'(j))) \tag{11}$$

where a represents a random value between 0 and 4.

Step 5: Each recruited unemployed bee continues to search new different solutions just around the leading bee's solution space similar with Step 2, and calculate their cost values.

Step 6: If the search time is larger than *Limit*, the employed bee abandons the solution, and re-initializing the parameters randomly and calculating the fitness function value.

Step 7: Store the best solution parameters and the best fitness function value.

Step 8: Enforce the chaotic search in the around of the best solution parameters based on (11) and calculate the fitness.

Step 9: If the termination conditions is not satisfied, choose another external perturbation, go to Step 2. Otherwise, output the optimal parameters and optimal cost value.

The detailed procedure is shown in Fig. 6.

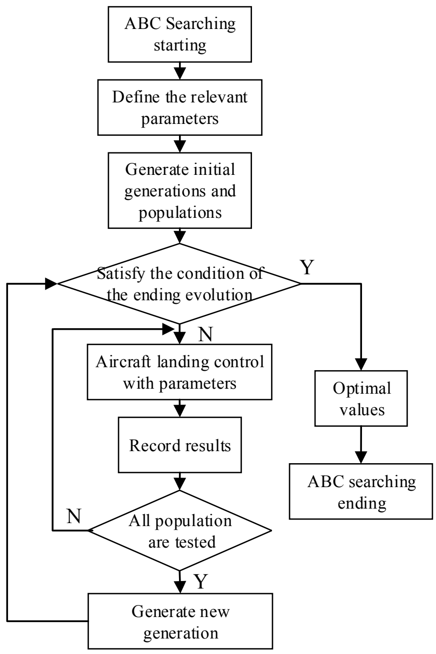

Fig. 6. The automatic landing system parameters tuning process based on CABC.

6. EXPERIMENTAL RESULTS

In order to investigate the feasibility and effectiveness of the CABC approach for tuning of automatic landing system parameters, a series of experiments are conducted under some constrained conditions.

Suppose that the aircraft starts the initial states of the automatic landing system as follows: the flight height is 115 *m*, the horizontal position before touching the ground is 2000 *m*, the flight angle is -3° , and the speed of the aircraft is 70 *m/s*. The initial vertical rate and angle of attack of the aircraft are set as zeros, and the referenced values are -2.5 *m/s* and 0.5°, respectively. The range of the throttle set is [-90 90].

The final optimal result generated by CABC and ABC are K_{CABC}= [K_h, K_{hd}, K_{hi}, K_1, K_2, K_3, K_4, K_5] = [0.0073, 0.0004, -0.0073, 3.2695, 2.0319, 1.6871, 8.8721, 0.0888] and K_{ABC}= [0.0084, 0.0004, -0.0078, 3.7832, 0.7629, 1.1808, 9.7774, 0.3627], respectively. The minimum fitness value of CABC and ABC are $J_{\min}^{CABC}$=0.2239 and $J_{\min}^{ABC}$=0.3457, respectively. Comparison of the simulation results between the CABC and the basic ABC are illustrated from Fig. 7. Fig. 8 shows the evolution curves of ABC and CABC.

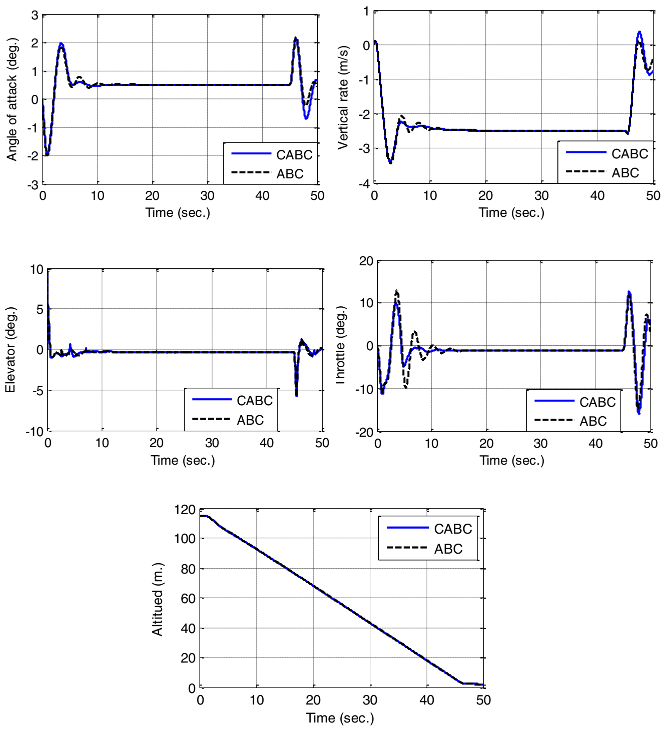

Fig. 7. Results of tuned controller parameters for automatic landing system based on ABC and CABC.

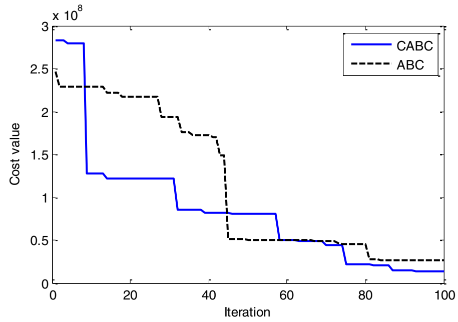

Fig. 8. Evolution curve comparison of ABC and CABC.

It is obvious that the aircraft experienced less perturbation by using the control gains generated by CABC, which means more stability. However, the first perturbation of angle of attack reaches to a maximum value (2°) at 3 second in Fig. 7, which means the aircraft may loss stability in the initial stage. The angle of attack reaches to the final position at about 10 second. The oscillations of vertical rate and throttle command are also reduced by using CABC.

The evolution curve shows that CABC can find a better solution. The standard ABC also plunges into a local optimal solution sometimes. The ergodicity of chaotic mechanism can help the basic ABC algorithm to jump out of the local optima.

Fig. 9 and Fig. 10 show the results from using varied wind turbulence speeds. The automatic landing system with CABC optimized gains can successfully guide an aircraft flying through wind speeds of 0-4*m/s*.

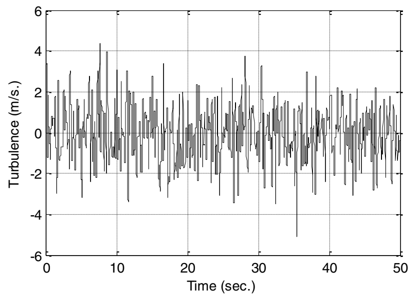

Fig. 9. Turbulence profile.

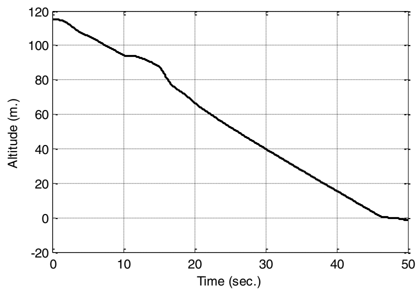

Fig. 10. Aircraft altitude response with turbulence.

From these simulation results, it is obvious that the proposed CABC approach is quite effective, and CABC could make the automatic landing system obtain a better performance than the basic ABC.

7. CONCLUSIONS

This paper presents an aircraft automatic landing system includes a vertical rate referenced guidance system and an angle of attack referenced approach power compensation system. CABC is an improved ABC algorithm for tuning the control parameters of aircraft automatic landing system, which can reduce the workload of the designers during the process of designing complicated aircraft control systems. In our proposed approach, a new fitness function is designed during design procedure. The feasibility and effectiveness of our designed automatic landing system has been also verified by a series of comparative experimental results.

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