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REVIEW

Review on guidance and control of aerospace vehicles: recent progress and prospect

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Abstract
This paper expounds on the development status and relevant works of control and guidance methods of the aerospace vehicle in recent years. The control difficulties and the solutions in the related results are introduced briefly. Moreover, the guidance methods are then expounded in detail according to the flight phases of the whole flight mission. Guidance methods are usually included in each phase, and the corresponding trajectory design theories are also introduced where necessary. In addition, the potential future development direction prospects. Based on the above, a brief conclusion is then made as a summary.

Keywords Aerospace vehicle · Combined cycle · Space flight · Control · Guidance

1 Introduction

With the vigorous development of the aerospace industry, aerospace vehicle, a kind of aircraft with fast flight speed, strong mobility, and wide coverage, has attracted extensive attention in various countries. Recently, significant progress and advances in the guidance and control technology have been achieved. This review article presents the confronting problems and their solution of aerospace vehicle guidance and control according to different flight phases, moreover, a potential progress trend is concluded.

Aircrafts based on combined-cycle power, with strong mission adaptability, is a future development direction for aerospace vehicles. They, among which the rocket-based combined-cycle vehicle is typical, can satisfy flight requirements of short acceleration maneuver and enduring efficient cruise by fully utilizing combined power's comprehensive performance advantages of high thrust-weight ratio and specific impulse. Compared with unpowered or traditional fire-powered aerospace vehicle, Combined Cycle vehicle boasts large flight airspace and airspeed span, drastic changes in a flight environment, and multiple constraints [1]. In addition, engine mode performance varies significantly from each other, and they are also coupled with flight state, resulting in a challenging trajectory optimization design process of Combined Cycle vehicles.

Generally, the aerospace vehicle has a relatively high lift–drag ratio when flying at a high Mach number (Mach number is greater than 5) during the re-entry phase. Still, due to significant changes in altitude and speed, the nonlinear characteristics of the aerodynamic and dynamic models of the vehicle are prominent. At the same time, complex flight environments, strong uncertainty interference, multiple physical constraints, and other factors bring significant challenges to the guidance and attitude control of the aerospace vehicle during the re-entry phase. The conceptual figure of aerospace vehicle is shown as Fig. 1 [2]. Its advantages are reflected in the professional sector: large combat airspace and wide range. Because aerospace vehicle flies near space at more than 20 km from the surface of the Earth, the atmospheric density is low, and the aerodynamic resistance is small, it can effectively and quickly strike all kinds of long-range targets worldwide and expand the combat range. It has fast flight speed and high maneuverability, which can shorten the detection time of enemy radar and the response

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Fig. 1 The conceptual figure of the aerospace vehicles from literature [2]

time of defense systems, and it has strong penetration ability. Flexible deployment and launch mode, high efficiency of task execution; the flight kinetic energy is significant, and it can produce stronger damage effectiveness than conventional vehicles under the condition of carrying the same mass warhead. The above advantages determine that the aerospace vehicle can be a long-range vehicle to efficiently complete various flight tasks such as surveillance, reconnaissance, and communication support. It has strategic deterrence and actual combat capabilities and is the ore force for rapidly and accurately achieving global long-range flight missions.

In the amateur sector, aerospace vehicles can be used as new intercontinental passenger/cargo vehicles to achieve faster speed, carry more and a wider range of global navigation than ordinary aircraft, and improve human lifestyle and living standards. Hypersonic cargo aircraft can conveniently realize the rapid and accurate remote delivery of high-value materials, improve transportation efficiency, and drive global economic growth. Hypersonic airliners can shorten passenger-travel time, improve work efficiency, and promote global integration. At the same time, the development of hypersonic technology provides a highly reliable, high-efficiency, low-cost, and energy-efficient way to enter and exit space. Steelant J et al. [3] propose the overall layout of an experimental powered high-speed aircraft, including its subsystems. The final vehicle layout can achieve different mission objectives. Especially based on hydrogen-powered scramjet, the aerodynamic propulsion balance of thrust $\geq$ drag and lift $\geq$ weight can be established under the cruising Mach number of $M = 7.4$, and good aerodynamic efficiency $L/D \geq 4$ can be guaranteed in a stable, adjusted, and controllable way. As a more controllable space vehicle, aerospace can be applied to outer space exploration.

The trajectory optimization design of the Combined Cycle has been researched since early in foreign countries. In the literature [4], based on the constant dynamic pressure idea, the ascent-trajectory design of the Combined Cycle is accomplished through trajectory optimization software POST. Based on the same idea in the literature [5], the flight mission profile of Lazarus, a single-state-to-orbit Combined Cycle vehicle characterized by horizontal takeoff and landing, is analyzed. Moreover, a desirable trajectory is presented through iteration. In Ref. [6], the Combined Cycle is introduced into the first stage of the two-stage-to-orbit vehicle with the intention of the highest fuel efficiency and maximum separation velocity. In addition, the trajectory in the ascent phase is optimized based on the pseudo spectrum, and the effectiveness is proved through simulations. Based on Refs. [6, 7] takes the Combined Cycle first sub-stage and rocket-powered second sub-stage into integrated consideration. Besides, it completes parameter optimization for aerodynamic shape, mass distribution, mode transition point, and sensitivity analysis through trajectory optimization.

The research results of trajectory optimization design for Combined Cycle aircraft in China appeared in 2006. Wang Houqing et al. [8] established the mathematical model of flight trajectory and mass analysis of the cruise vehicle powered by a Combined Cycle and solved it for specific technical parameters. The results show that the Combined Cycle cruise vehicle is feasible when the inert mass coefficient of the aircraft is less than 0.6. Zhan Hao et al. [9, 10] introduced the Combined Cycle as the launch vehicle's first stage. In addition, the flight trajectories of Combined Cycle powered horizontal takeoff, vertical takeoff, and pure rocket-powered vertical takeoff were calculated and compared, whose results show that compared with pure rocket power, the Combined Cycle can effectively reduce the fuel consumption of the vehicle. The above research results make a beneficial exploration for the trajectory design of Combined Cycle vehicles, but the mutual coupling between engine performance and flight state needs to be addressed. Lu Xiang et al. [11] considered the coupling between Combined Cycle engine performance and flight state. They proposed a trajectory design method based on the Mach number and dynamic pressure reference curve.

This method is divided into two steps: first, determine the Mach number and dynamic pressure reference curve; then solve the actual control variables according to the designed reference curve. Xue Rui et al. [12] took the first sub-stage of the Combined Cycle of the two-stage-to-orbit launch vehicle as the research object. They divided its ascent trajectory into a non-constant dynamic pressure section and a constant dynamic pressure section. Moreover, they used a genetic algorithm and analytical method based on the height step to design the trajectory. Yan Xiaodu et al. [13] derived the H–V reference curve for constant dynamic pressure ascent to ensure the Combined Cycle engine's stable operation. They designed the guidance law for reference curve tracking based on the feedback linearization method. Jia Xiaojuan et al. [14] considered ascent from zero altitudes, dividing the ascent trajectory into the takeoff climb phase, constant dynamic pressure phase, and constant heat flow phase. Moreover, they also counted overload, dynamic pressure, and heat flow constraints, respectively. According to this, they designed the H–V reference profile and the nominal trajectory tracking guidance law by feedback linearization method. The above studies consider the coupling between Combined Cycle engine performance and flight state. Still, they do not adopt an optimization algorithm, and the designed trajectory is conservative, which does not fully exploit the aircraft's overall performance. Li Xiang et al. [15] used a non-uniform rational B-spline to parameterize the design variables and adopted a genetic algorithm to optimize the ascent and cruising range of a Combined Cycle hypersonic missile. As for the Combined Cycle + Rocket two-stage-to-orbit vehicle with horizontal takeoff, Ruan Jiangang et al. [16] proposed an aircraft trajectory optimization method based on an augmented Lagrangian genetic algorithm. These two papers optimize the trajectory of Combined Cycle aircraft, but the process constraints such as dynamic pressure, overload, and heat flow are not fully considered in the optimization process. Gong Chunlin et al. [17–20] took the Combined Cycle suborbital reusable vehicle as the research object. To solve the problems of multiple working modes and the complex constraints of such aircraft, they adopted the pseudospectrum method to optimize the trajectory of the ascent phase to minimize fuel consumption. Zheng Xiong et al. [21] proposed a layered nested optimization strategy of "particle swarm optimization + pseudospectrum method" for the global trajectory optimization problem of Combined Cycle aircraft, which could optimize the overall mission profile and flight trajectory at the same time. Zhou Hongyu et al. [22] introduced the reinforcement learning mechanism into ascent-trajectory optimization of the combined power vehicle, improving the efficiency of the particle swarm optimization algorithm.

Table 1 The characteristics of the usual control methods

Control methods	Characteristics	Details
PID	Simple algorithm, high reliability, easy-to-adjust parameters Able to cope with steady-state error and linear systems	Ensure error function approaches zero through three kinds of calculations: proportion, integration, differentiation, thus achieving desirable control effects; Most widely used in flight control; Undesirable robustness and accuracy in comparison to other newly proposed methods
Robust control	Reliability and stability are primary goals Excellent adaptability to the uncertainties in the system	Suitable for systems with large uncertainties and small stability margin; Available without exact process model; Usually unable to achieve best control effects with low steady accuracy;
Dynamic inverse method	Effective in coping with the nonlinear parts in the model by the inverse calculation to the system	Realize the accurate linearization of some nonlinear components in system by nonlinear cancelation; Especially suitable for flight phases like transonic segment;

2 Research status of control methods

This section mainly discusses two subsections. Section 2.1 briefly introduces the control difficulties; Sect. 2.2 discusses the usual control ideas and their related work.

The following Table 1 lists the usual control methods and their respective characteristics.

Table 1 (continued)

Control methods	Characteristics	Details
Active disturbance rejection control	Reduce internal and external interference to improve robustness Independent from the accurate identification of interference parameters	Identify disturbance or uncertainties in system by extended state observer (ESO) and then introduce the perturbation into system input; Show strong robustness to interferences;
Sliding mode control	Strong robustness to system parameter changes and interference	Transform the Lyapunov function of two variables into single-variable by introducing a sliding mode surface (actually an error tracking function); Usually used to improve control accuracy and robustness
Adaptive control	Determine the control parameters by disturbance identification and analysis to stay stable and reliable online	This control system can online determine the corresponding control effectors according to the disturbance on the vehicle to realize stable flight or precise path tracking

2.1 Control difficulties

Unlike the traditional vehicle, aerospace vehicles' flight environment (atmosphere density, velocity) changes dramatically leading to a strong uncertainty of the dynamics model; aerodynamics and thermodynamics are strongly coupled with multiple constraints. The problems mentioned above bring much trouble to the control of the vehicle throughout the whole process.

(1) It is difficult to control the fine attitude under the condition of strong uncertainty in near space.

On the one hand, due to the complex environmental characteristics of high-speed flight in near space, the mechanisms of rarefied gas effect, high-temperature gas effect and flow transition have not been fully mastered, and the consistency difference between ground and sky in ground tests is large, which is reflected in the strong uncertainty of the dynamics model of hypersonic aircraft. On the other hand, due to the significant influence of aerodynamic attitude Angle on the intake characteristics of the subsonic/supersonic mode engine, the deviation of attitude control may lead to the decline of propulsion performance or even the engine ignition. The control accuracy of Angle of attack and sideslip Angle is high, and the design of fine attitude control is necessary.

(2) The flight-stability characteristics change dramatically in the wide-speed domain.

Compared with conventional aviation aircraft, the flight envelope of hypersonic aircraft is greatly expanded, and more fuel consumption will lead to greater changes in the mass, center of mass, and moment of inertia of the aircraft. In addition, the pressure center of the aircraft will move with the increase of Mach number, and the static stability will decrease with the increase of Mach number. The control efficiency, stability, and damping characteristics of the aircraft will change greatly in the wide-speed range, resulting in greater changes in the characteristics of the controlled object and drastic changes in the control characteristics, which bring difficulties to the design of wide-speed range flight attitude stability control.

(3) Strong demand for integrated aircraft/engine cooperative control.

The highly integrated configuration of the aircraft body/engine of hypersonic aircraft makes the coupling between flight dynamics, aerodynamics, and propulsion dynamics/thermodynamics stronger, mainly reflected in the following aspects: first, wide-speed range aerodynamic/propulsion coupling; second, the thrust characteristics of the engine mode conversion and the thrust/thrust moment characteristics are different, and the dynamic stability characteristics change non-smoothly with the thrust mutation and hysteresis characteristics in the mode conversion process, which has a significant impact on the attitude stability control; third, the frequency band overlap coupling of the flight control system and the engine control system; fourth, the frequency band overlap coupling of the aircraft control system and the engine control system. Fourth, the coupling of engine safety protection tasks and flight control tasks. When the aircraft task requirements reach the flight performance boundary, it is possible to trigger the engine safety protection control system, reduce the quality of thrust-command tracking control in the flight control system, and focus on meeting the protection requirements of engine overtemperature, oil rich and poor fire and inlet not starting. There is a contradiction between engine safety protection and flight control system response ability. In summary, it is necessary to carry out the integrated control design and comprehensive simulation analysis of flight control loop/engine control loop from the perspective of flight-launch integrated control.

4) Elastic control problem under relaxed static stability conditions.

The static stability of wide-range hypersonic aircraft decreases with the increase of Mach number. To achieve full flight envelope static stability, the static stability of low speed segment needs to be very high, which leads to poor lift and drag performance and maneuverability of the aircraft. Therefore, the relaxed static stability design is the future development direction. However, to overcome static instability, the angular position (overload) feedback gain usually increases, leading to an increase in the frequency band of the control system. On the other hand, the structural elastic vibration frequency caused by the enlargement of the lightweight structure decreases, and the elastic modal frequency band of the body is closer to the frequency band of the control system. The traditional filter design will make the rigid body stable control performance and elastic suppression cannot be taken into account, and the design of elastic static instability control faces challenges, as shown in Fig. 2.

Modern aerospace vehicles often employ large, complex and lightweight structures which result in these structures being extremely flexible and having low-frequency fundamental vibration modes. These bring challenges to traditional control methodologies. Therefore, there is urgent need to develop more effective control methods.

2.2 Related work

The main idea of control system design includes optimal, adaptive, and robust control. Optimal control is to solve the problem of ensuring the optimal closed-loop performance of the system when the model form and parameters are known; Adaptive control is to solve the problem of realizing closed-loop stability when model parameters change; Robust control is to solve the problem of how to eliminate the influence of uncertain, unknown dynamics on the closed-loop stability of the system. Therefore, the accuracy of the controlled object's model information determines the control system's design idea.

According to the relationship between control law design methods and model information, control system design methods can be divided into three categories: dependent model, partially dependent model, and completely independent model design methods. Many control laws are designed based on known models, such as pole assignment, linear quadratic regulator (LQR), linear matrix inequality (LMI)-based H∞ controllers, precise feedback linearization, nonlinear dynamic inversion (NDI), etc. However, there is no accurate known system model in practical application. Therefore, the requirements for closed-loop robustness are added to the above methods. The control law design method of partial model dependence reduces the need for system modeling accuracy and has strong robustness. In addition, with the development of digital computing technology, data-driven controller design methods (independent of models) have also emerged, including active/auto disturbances rejection controller (ADRC), model predictive control, adaptive dynamic programming, etc. The specific research status is as follows.

The last few decades have witnessed tremendous advances in control techniques such as robust H_2/H_∞ control, adaptive control, and sliding mode control, which have been successfully applied to handle difficulties that are thought to be complex for aerospace vehicle systems. For example, K Lu et al. [23] propose a new sliding mode controller to ensure the asymptotic convergence of the attitude and angular velocity tracking errors based on classical sliding mode control idea. In the work of Bauer W, the Reaction Control System (RCS) is proposed to cope with the low effectiveness of the aerodynamic surfaces at an altitude of over 70 km [24].

As for control law design, "PID control law design + gain scheduling" is still the mainly used method [25–27]. The lateral control scheme [28] of "heading control roll" was used in the early lateral control of the space shuttle. While there exists the problem of excessive dependence on the heading RCS, therefore a lateral control scheme with anti-aileron control above Mach 3 and conventional control below Mach 3 was proposed after several flight tests by Kirsten P to deal with that issue [29]. Apart from that, some combined control methods also emerge as effective ones for especially flight phases with complicated aerodynamics changes and large velocity span such as orbit-entry phase and re-entry phase. Among them, one of the control schemes of X-33 aircraft is the fusion of nonlinear dynamic inverse (NDI) and neural network intelligent control [30–32], and the test results do prove the excellent effects and significant potential of combined control ways in aerospace vehicle control industry. At the same time, sliding mode control [33–36], adaptive feedback linearization control [37–39], and trajectory linearization control [40, 41] are also proposed. For some examples, a novel adaptive-gain multivariable generalized super-twisting (AMGST) controller and a fixed-time disturbance observer (FTDO) are proposed for reusable launch vehicle (RLV) subject to model uncertainties, input constraints, and unknown mismatched/matched disturbances. They divided the attitude motion of RLV into outer-loop subsystem and inner-loop subsystem. The former is for outer-loop and latter for inner-loop.

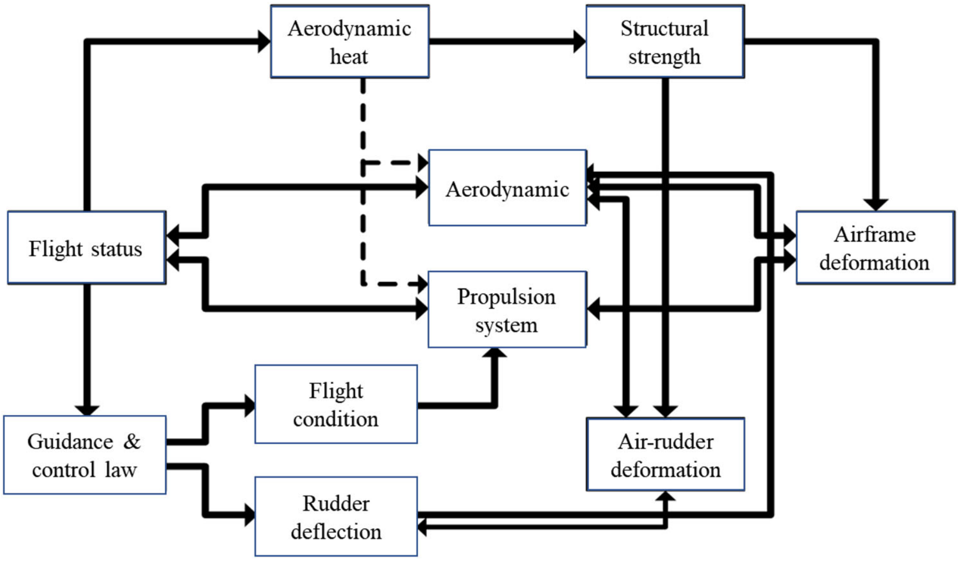

Fig. 2 The relationship between elastic deformation and elastic vibration on dynamics

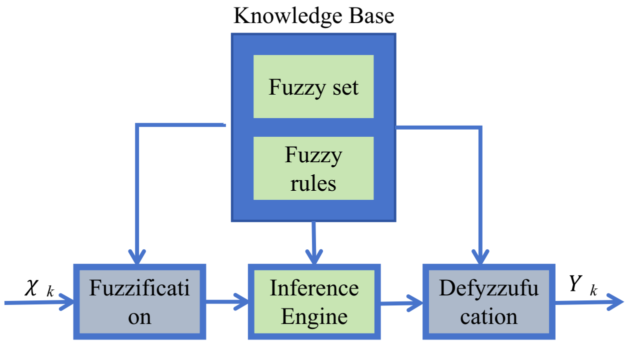

Fig. 3 The structure of the self-tuning PID controller

In recent years, a wide range of research has been conducted on the VTHL horizontal return control method. These researches can be mainly divided as follows, among which the combined approach is particularly attractive.

Self-tuning PID method: The classical PID method is combined with optimization algorithms (such as genetic algorithm, neural network) or fuzzy mathematics to equip PID controller parameters with the self-tuning ability to improve adaptability [42] in Fig. 3. As a basic control design method, this method can be applied in all flight phases to enhance the disturbance adaptability.

Sliding mode control: It is easy to achieve convergence in a limited time through sliding mode control, but the control chattering can't be eliminated. Therefore, the system's unmodeled dynamics may be aroused. But the sliding mode control variable structure system has progressed in the control of space aircraft [35, 43, 44]. When the nonlinear re-entry characteristics are large, or the Angle of maneuver is large, the system can slide to the stable origin according to the expected dynamic features. To a certain extent, this method boasts advantages in disturbance rejection and attitude tracking.

Sliding mode control is one of the effective ways to solve the re-entry attitude control problem of the launch vehicle under the influence of parameter uncertainty and disturbance because of its fast response, high control accuracy, strong robustness, and other advantages. Reference [45] designed a multivariable adaptive super-twisting finite-time sliding mode control law considering the disturbance torque. Reference [46] uses a finite-time ESO to observe and compensate for the disturbance during reentry, reducing the sliding mode control's chattering problem. To make the upper bound of convergence time independent of the initial state of the system, that is, to achieve fixed-time convergence, reference [47] designed a control law based on nonsingular terminal sliding mode and fractional order state feedback so that the attitude control error converged within a fixed time. Reference [48] introduced fixed-time convergence observer (FxTESO) in sliding mode control to ensure fixed-time convergence and reduce chattering of control quantity. Reference [49] comprehensively adopted an accurate, robust differentiator and terminal sliding mode method to design fixed-time control law and introduced a compensation function to avoid singularity of control quantity. However, under the action of the above fixed-time sliding mode control (FxTSMC) method, the upper bound of the system convergence time is determined by a complex function composed of multiple control parameters, which is difficult to be directly determined by a simple, functional relationship, bringing some difficulties to the design work.

Adaptive control: Lyapunov theory is used to design the control algorithm, and the control strategy is determined by information collection, parameter identification, and performance analysis, and the control parameters change with time.

Reference [50] designed a robust adaptive controller for a wide range of nonlinear systems with dynamic uncertainties; Reference [51] proposed the adaptive control of nonlinear systems represented by input–output. Subsequently, Reference [52] proposed a robust adaptive algorithm for nonlinear systems without continuous excitation; on this basis, reference [53] used neural networks to approximate the nonlinear system represented by nonlinear parameters through online and offline training, and realized robust adaptive control of nonlinear uncertain systems by designing robust control terms. Based on [51, 54] considers the robust adaptive control of nonlinear systems with unmodeled dynamics and nonlinear parameters. This method is often used with others to improve flight reliability and adaptability through the online identification and compensation control of disturbance, and has been focused on by many researchers subject to the control of aerospace vehicles.

Robust control: Considering the deviation between the actual system and the mathematical model, a specific control structure is used to meet the stability and other performance indicators in the deviation state [55–57]. Robust control has high requirements for stability and design processes. It's easy to implement and can be applied to unpowered flight segments to improve aerodynamics robustness with little aerodynamic influence.

Dynamic inverse method: It realizes the feedback linearization design of a nonlinear control system. In addition, it has a desirable control effect for the flight phase with strong nonlinearity, such as large-Angle-of-attack re-entry and transonic speed [58]. A nonlinear disturbance observer (NDI) constructs an inverse output system by designing virtual control variables in the inner ring [59]. To compensate for unmodeled dynamics and external disturbances, Reference [60] proposed the idea of NDI design based on a nonlinear disturbance observer. Using NDI to estimate the unmodeled dynamics of the model, a compensating controller (CC) is designed to improve the robustness of the closed-loop system.

Active disturbance rejection control (ADRC): Consisting of Tracking differentiator (TD), Extended state observer (ESO) and Nonlinear state error feedback (NLSEF). It can reduce internal and external interference to improve dynamics robustness without accurately identifying interference parameters [61]. The control structure in literature [61] is shown in Fig. 4, in which z_{11} is the transition of reference signal from TD (tracking differentiator), which can avoid violent variation of tracking error. z_{12} is the one order derivative of z_{11}. z_{21} is the estimation of system feedback; z_{22} is the one order differential of z_{21}; z_{23} is the estimation of total disturbance and it will be compensated by the compensation coefficient $1/b$. $u(t)$ is the output of ADRC.

In addition, based on neural network learning and fuzzy control technology, improved control methods represented by preset performance control and -ime control have been proposed, which further expand the idea, but are yet to be verified.

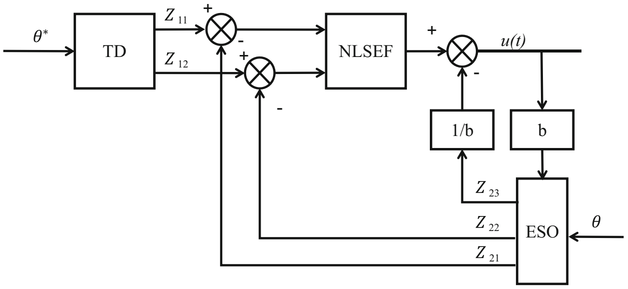

Fig. 4 The structure of the ADRC controller

3 Research status of guidance methods

Generally, aerospace vehicles' guidance is roughly divided into the ascent phase, orbit-entry phase, re-entry phase, terminal area energy management phase, and landing phase. The following subsections will introduce the development status of the guidance at each stage, as shown in Fig. 5.

3.1 Ascent guidance

The combined dynamic climb stage refers to the flight stage from the takeoff of the assembly to the first and second stage separation. Due to the flight in the dense atmosphere and near space and the wide-speed domain multi-mode aerodynamic/propulsion coupling characteristics, the current guidance technology mainly focuses on the nominal trajectory tracking guidance technology, and the research on adaptive guidance technology based on online programming is in the initial stage.

Due to the narrow flight corridor, the mostly used guidance techniques focus on nominal trajectory tracking guidance. The computational guidance method based on online trajectory planning can also be applied, but its solution stability could be better. In addition, reasonable constraints and initial values need to be set, which makes it complex to use.

In literature [62], the nominal trajectory of the ascent stage is divided into stages according to the flight time. Then the differential method is adopted to solve the two-point boundary constraint problem to get the trajectory control quantity. In literature [63], flight trajectories were divided according to time, Hamiltonian functions were constructed, flight constraints were converted into costate equations, and optimal control theory was adopted to solve trajectory control variables. Sun Chunzhen et al. [64] proposed the guidance method of the ascent stage based on finite differentiation,

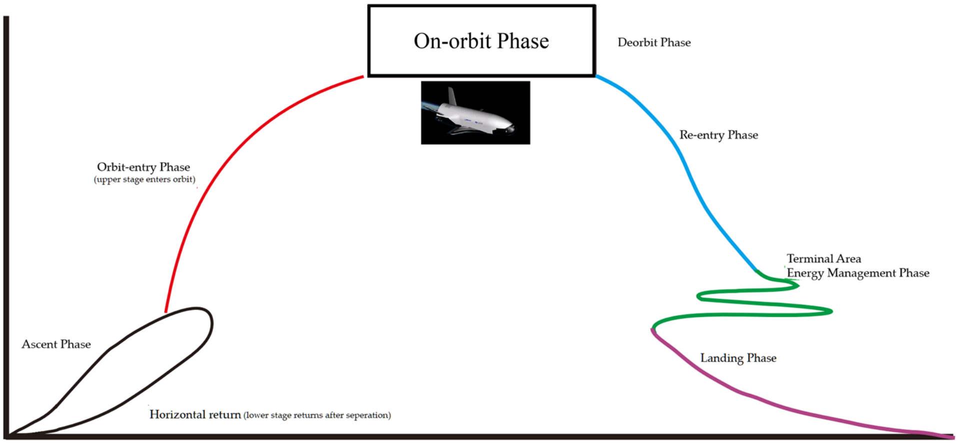

Fig. 5 The whole flight mission profile of the two-stage-to-orbit aerospace vehicle

which generates guidance instructions online and has specific adaptability under the fault state. Yan Xiaodong [65] proposed the constant dynamic pressure climbing method.

In the early stage, the guidance methods of the ascent stage were all open-loop guidance, and the position, velocity, and attitude commands during orbit entry were obtained through offline trajectory planning. The typical methods include Iterative Guidance Mode (IGM) and Powered Explicit Guidance (PEG).

Based on optimal control theory, IGM can realize the optimal attitude Angle planning through the iterative calculation of analytic expression [66–69]. The iterative guidance method with terminal attitude constraints was first used in the CZ-2F/T3 launch mission in September 2020. Moreover, remarkable advancement and progresses were also achieved during the application. CZ-7 adopts predictive correction IGM, which can omit the final velocity correction system to achieve a high-precision direct orbit under large thrust.

PEG is a semi-analytical predictive correction algorithm independent of nominal trajectory. It was proposed based on linear tangent guidance (LTG) to cope with emergencies such as failure and return.

In 2021, the autonomous guidance method (AGM) theory was formally introduced by Song Z Y et al. [70] at China Space Congress Space Intelligent Autonomous control academic forum. It can generate real-time guidance command that meets intricate constraints and terminal requirements according to the flight status of the vehicle. Therefore, it can handle complex flight statuses with time-varying and nonlinear constraints.

3.2 Orbit entry guidance

The stage of rocket power entry into orbit refers to the stage after leaving the atmosphere until it enters the predetermined orbit. Since the aircraft has left the atmosphere, the constraint parameters, such as dynamic pressure, heat flow, and overload, all decline or disappear, and the constraint is gradually relaxed. Therefore, starting from the orbit entry, the trajectory design and guidance target are often aimed at the terminal state and accuracy.

The basic idea of perturbation guidance design is the same as that of the nominal trajectory tracking guidance of the combined dynamic climbing stage. The difference lies in the planning and design of the benchmark flight trajectory, which will be discussed elsewhere.

3.2.1 Iteration guidance

Iterative guidance is widely used in orbit guidance. Based on the optimal control theory, it predicts the terminal state by calculating the remaining time and determines the optimal flight program Angle based on this [71]. Compared with perturbation guidance, iterative guidance does not depend on a nominal trajectory but satisfies terminal constraints by predicting the terminal state and giving a flight path. The iterative guidance theory was first proposed by Doris C. Chandler [72] in 1967. Ru Jiexin [73] showed the detailed reasoning process of the iterative guidance theory. Chen Xinmin [74] focused on applying the iterative guidance method on carrier rockets and pointed out its advantages of high precision and universality of the algorithm for different tasks.

Han Xueying [75] proposed an iterative guidance method with in-orbit attitude constraints. Based on traditional iterative guidance, a square term of the remaining time and its parameters were added to the expression of control variables to cover the terminal attitude constraints. Based on the optimal control theory, Wang Zhi [76] deduced the explicit analytical solution of the control variables in the orbit segment. Compared with the nominal trajectory guidance, it can cover a more extensive deviation range, has strong adaptability, and requires less calculation. Hao [77] divided the in-orbit section into iterative guidance and rapid attitude adjustment sections. In the iterative guidance section, the classical iterative guidance method was used. The terminal attitude Angle was estimated at the same time.

3.2.2 Trajectory guidance method based on convex optimization

Considering that only second-best guidance instructions can be obtained in each step in the iterative guidance calculation process, the academic community has sought online planning methods with better performance. Convex optimization is a fast optimization method with relaxed constraints. It was first proposed by Acikmese et al. [78–80] to design a Mars landing trajectory. The core idea of convex optimization is to transform non-convex models and constraints into convex ones through linearization and relaxation and then relax the trajectory design problem into a convex problem, which the convex optimization solver solves. The commonly used convex optimization model in trajectory design is Second-Order Cone Programming (SOCP). In literature [81, 82], the rendezvous and docking problem is transformed into a series of SOCP subproblems, called sequences, based on the background of rendezvous and orbit entry. The method to solve this series of subproblems is called sequence convex optimization. The solution vector of the previous subproblem will be used for the next convexation. The original nonlinear and non-convex problems are transformed into a series of convex subproblems by sequential convex optimization, and the solutions of the subproblems are guaranteed to converge to the keys of the original problems [83].

In the orbit phase, the spacecraft may face failure and fail to achieve the original mission objectives. The main causes of failure include: the engine does not fire on schedule, aiming information error, navigation system failure, engine thrust loss, etc.

Literature [84, 85] considers guidance under fault and provides adaptive guidance strategy under fault. Chang Wuquan [86] proposes that faults can be divided into two categories: non-energy and energy faults, and proposes that large energy faults often need online guidance and correction. Non-energy faults and small energy faults can achieve the goal after degradation through online trajectory planning and guidance law reconstruction, at least to ensure the partial success of the mission to avoid losses to a certain extent. Song Zhengyu [87] proposed a convex subproblem construction method for trajectory reconstruction and guidance problems of rockets under the fault of ascending stage. The residual fuel is calculated, and the residual carrying capacity is evaluated using the iterative guidance method. Conversely, the convex optimization results can give guidance instructions; conversely, the task completion degree under the fault can be assessed. Instead, it solves the optimal elliptical rescue orbit and updates mission objectives to reduce losses.

3.3 Re-entry guidance

The re-entry stage is when the aircraft re-enters the atmosphere after deorbiting. The re-entry process goes through a vacuum and atmospheric environment. The flight environment is relatively complex, mainly reflected in the large variation range of velocity domain airspace, few adjustable control variables, and high precision requirements.

Since the in-orbit operation has the highest function and potential energy in the mission profile, reentry is easier to break through dynamic pressure, overload, and heat flow constraints than other flight segments. Based on these constraints, flight corridor design can be carried out. On the other hand, the goal of the re-entry section is also to aim at the terminal state and drop point accuracy. Considering the relationship between constraints and heeling Angle, the constraints can be converted into heeling Angle amplitude profile to meet the constraint requirements of trajectory design.

The design of the vehicle re-entry guidance law aims to establish a closed-loop system between the guidance command and the flight trajectory to ensure that the vehicle can safely transfer from the initial re-entry point to the target point under the premise of meeting the re-entry flight requirements, and provide feasible re-entry guidance for the attitude control system. The re-entry guidance technology has attracted attention since the early 1960s. In recent years, The Marshall Space Flight Center of the United States proposed Advanced Guidance Control, and the Air Force Laboratory of the United States studied Integrated Adaptive Guidance & Control. The European Space Agency (ESA) conducted research for advanced diagnosis for sustainable—able flight guidance and control.

The commonly applied guidance methods include trajectory tracking, predictive correction, and intelligent re-entry guidance.

3.3.1 Trajectory tracking guidance

In the 1960s, Moe [88] proposed a re-entry trajectory estimation method. Subsequently, Bate [89] proposed an empirical formula for bullet-type reentry, and Blum [90] proposed a bullet-type re-entry trajectory planning method based on the plane earth model. Due to the characteristics of large overload and high heat flow, ballistic re-entry cannot be directly applied to the re-entry process of lift aircraft. Therefore, some scholars have proposed establishing flight corridors based on constraints and ensuring compliance with constraints through trajectory design inside the flight corridors. Typical re-entry terminal constraints include terminal height, velocity, and remaining range constraints, which can be converted into constraints on the heeling Angle amplitude combined with the reentry dynamics equation.

According to the characteristics of the re-entry corridor and the aerodynamic quality of the research object, several scholars [91, 92] divided the re-entry process into an initial descent section, temperature control section, constant resistance section, and transition section on the drag acceleration-velocity profile, and realized the re-entry trajectory design by solving the profile parameters. Based on the time-varying describable heeling Angle constraint, some scholars also used the optimization method to design the re-entry trajectory. Han [93] used the Radau pseudo-spectral method, and Tian [94] used the indirect Legendre pseudo-spectral method to generate the re-entry trajectory.

With the deviation of the actual trajectory and nominal trajectory (state deviation) as input, the size of the control variable is adjusted by the deviation value, and the controller coefficient is adjusted according to the influence of the control variable on the state variable. Yang Xiaolong [95] compared the results of PD control and PID control in drag acceleration profile tracking, and Hu Jiansue [96] proposed a fast design scheme for re-entry orbit, based on which PID tracking control was carried out in terms of lift–drag ratio, altitude, velocity, and its derivative and integral terms. Zheng [97], Ge [98], and Dai [99] have presented a tracking guidance method based on LQR, the longitude and latitude error of which are both within 0.1°, meeting the guidance accuracy requirements.

The offline trajectory guidance in the early years was two-dimensional, in which the lateral and longitudinal guidance laws were designed, respectively. It realizes longitudinal guidance through flight profile tracking. Moreover, lateral guidance should be achieved through lateral motion logic. The mainly used profile tracking methods are listed as follows: linear feedback guidance [100–102], Tracking guidance method based on predictive control [103–105].

Three-dimensional offline trajectory guidance became focused due to the weak maneuvering ability of two-dimensional guidance. Chen D et al. [106] present a three-dimensional trajectory generation algorithm. The altitude vs. velocity profile is then planned, and the flight path Angle and bank Angle are obtained based on that. This guidance method will not fully exploit the vehicle"s maneuverability because we can only realize maneuver motion by controlling flight path Angle and bank Angle. As a result, the three-dimensional offline nominal trajectory guidance based on optimal trajectory solution is proposed to solve the problem. Based on RLV state quantity deviation, the issue of re-entry trajectory tracking is transformed into a state adjustment problem of the Linear time-varying (LTV) system [107]. Based on the obtained LTV system, a reentry guidance law based on a rolling Time domain prediction algorithm has been designed. In the work of G Dukeman [108], guidance gain is designed for the LTV system mentioned above based on Linear Quadratic Regulator (LQR). B Tian et al. [94] present a re-entry guidance method based on the indirect Legendre pseudospectrum method to calculate the real-time guidance gain under different flight statuses.

No matter the two-dimensional or three-dimensional offline trajectory guidance method, it cannot cope with emergencies and meet the requirements of flight missions. Therefore, it is necessary to adjust the trajectory in real-time when the flight conditions and needs change and calculate a new reference trajectory as the target of tracking guidance, that is, online trajectory guidance with the improvement of the trajectory optimization algorithm's performance and airborne computer's processing power, trajectory design changes from offline to online.

Literature [109] conducted fast trajectory planning between waypoints by setting waypoints. It guided the aircraft to the next waypoint by hybrid guidance in the local trajectory between waypoints, as shown in Fig. 6. Rapid online trajectory generation based on convex optimization is also widely applied in re-entry guidance due to its relatively high calculation efficiency. Liu [110] proposed a SOCP-based approach to the re-entry problem, made the model and process of the re-entry vehicle convex, and proved its global convergence. Wang [111] proposed a sequence convex optimization method based on the research of Liu, which transformed the re-entry problem into a series of convex subproblems and then solved them. In addition, there is a no-fly zone in the RLV reentry and return process. The literature [112] proposed an improved A* algorithm to realize the real-time trajectory planning process. A dynamic optimization guidance law was established based on the aircraft model considering the no-fly zone so that the aircraft could autonomously avoid the no-fly zone.

3.3.2 Predictive correction guidance

The basic idea of prediction correction guidance is to obtain the terminal state information based on the given heeling Angle instruction and then compare the terminal state brought by these predictions with their corresponding constraints to get the best heeling Angle instruction iteratively. Prediction-correction guidance is generally divided into longitudinal guidance and lateral guidance. The prediction part works in the longitudinal guidance part and iterates the optimal heeling Angle instruction of the current step. The lateral guidance module controls the symbol of the heeling Angle based on the defined transverse range to avoid deviation from the flight direction.

The predictive correction guidance method can be divided into analytical prediction–correction guidance and numerical prediction correction guidance according to the working mode of the prediction link. Analytical expressions calculate the terminal state. Zeng Zhengxin proposed the concept of

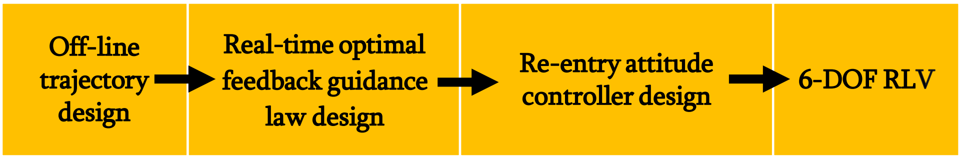

Fig. 6 The controller structure of fast trajectory planning between waypoints

energy factor in the document [113] and derived the analytical solution of the terminal range to be flown on this basis. The obtained analytical solution shows that when the initial and non-energy are given, the range to be flown depends on the lift–drag ratio and the heeling Angle. Therefore, the inclination Angle iteration can be carried out by calculating the distance to be flown by the given inclination Angle and comparing it with the distance to be flown by the final section. Meanwhile, an Angle of attack command adjustment method is also proposed in this paper, which takes the height as the state quantity and adopts PD control to adjust the Angle of attack so that the terminal height constraint is easier to meet.

In literature [114], the analytical solution of the jump trajectory is solved based on the matched progressive expansion. Since the re-entry process starts from the area dominated by gravity and then enters the area dominated by aerodynamics, a unified solution cannot be directly obtained. To solve this difficulty, independent solutions must be brought into each area and fused into a unified solution. In this way, the speed and track Angle of the whole course can be obtained, and the distance can be calculated based on this. The deviation of speed and distance determines the control command.

The terminal state is obtained by numerical integration in the prediction part of numerical prediction correction guidance. Shen [115] introduced a lateral guidance strategy in detail, defining the distance to be flown as the surface distance between the current position and the course calibration cylinder and defining the transverse distance through the distance to be flown and the course Angle. Xue [116] applied this lateral guidance strategy and proposed a longitudinal one, defining the surface distance between the terminal and the course calibration cylinder as the remaining distance. The terminal longitude and latitude are predicted by numerical integration, and then the remaining distance is obtained, and the inclination Angle is iterated. Lu [117] applied prediction–correction guidance to aircraft with low-lift structures and achieved high accuracy.

Zeng [118] obtained the solutions of the track Angle and velocity through the existing dynamics equations, reducing the dimension of the dynamics equation to be integrated and improving the calculation efficiency. Brunner [100] compared fully numerical predictor–corrector entry guidance (FNPEG) with Apollo spacecraft jump trajectory guidance and concluded that the FNPEG algorithm is very robust. It also works well for the mission with large range dispersion and long range, but the jump trajectory guidance only works well for the task with a range greater than 3000 km.

Many scholars have improved prediction correction guidance for more specific task forms. Zhao Jiang [101] and Wang [102] added the no-fly zone restriction into the process constraint, considering the problem of the no-fly zone during actual flight. Wang Xiao [103] believed that the traditional prediction correction method takes terminal energy as the constraint, which cannot entirely accurately reach the speed and height constraint, and the mismatch between speed and height often occurs at the terminal. He concluded through the formula that a larger range usually corresponds to a larger terminal height and a smaller heeling Angle profile.

The analytical algorithm runs fast, but it needs to derive the analytical solution of the terminal state. Numerical algorithms run relatively slowly but do not require the derivation of terminal state analytical solutions and have few restrictions on use. With the rise of artificial intelligence (AI) and neural networks, some scholars proposed improvement measures for numerical predictor-correction algorithms. Ran Maopong [104] proposed a predictor-correction guidance method based on the adaptive neural fuzzy system. The influence of the change of heeling Angle on the remaining terminal range was obtained through massive data training. ANFIS tool was used to automatically generate an adaptive neural fuzzy controller to replace the prediction function. Li [105] proposed a data-driven prediction–correction guidance logic. By introducing a neural network predictor, this algorithm effectively overcomes the contradiction between guidance accuracy and instruction generation time which has existed for a long time in the existing numerical prediction guidance methods.

3.3.3 Intelligent guidance

In the latest research, some scholars also proposed using neural networks for online trajectory design and tracking guidance. A two-step scheme is proposed to address the real-time trajectory planning of aerospace vehicles in the re-entry stage. Chai [119] first used a fuzzy multi-objective transcription method to generate the optimal trajectory of the H–V (height–velocity) profile. Then, a deep neural network (DNN) is trained using the generated optimal trajectory, and the neural network generates guidance instructions in real-time. The DNN controller is compared with other existing optimization techniques in the simulation. Simulation results verify the feasibility and reliability of the proposed method

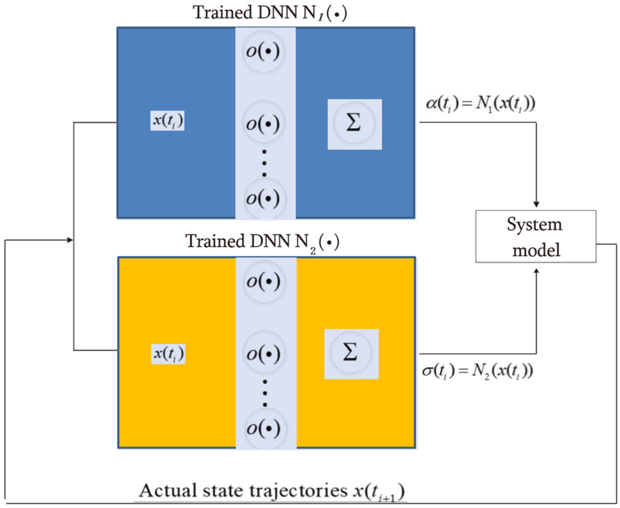

Fig. 7 The DNN-based control structure by Chai [118]

Table 2 The characteristics of the usually used guidance method in the re-entry phase

Guidance Method	Advantage	Disadvantage
Trajectory tracking guidance	Simple to implement; low requirements on the computer on board	A specific time for trajectory calculation and writing into the computer (undesirable for the fast response on the battlefield); unable to cope with the error by disturbance and emergency (such as mission changes)
Predictive correction guidance	Stronger flexibility and robustness compared with traditional trajectory tracking guidance; autonomy of online real-time instruction generation	Excessive computing may sometimes cause the non-convergence phenomenon
Intelligent guidance	Higher terminal state prediction efficiency	Still in infancy; dependence on the model and numerical simulation

in aerospace vehicle re-entry guidance. The control structure is shown in Fig. 7. The characteristics of the usually used guidance method are shown in Table 2.

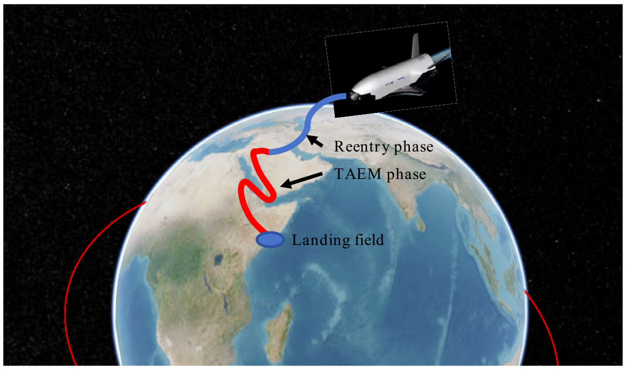

Fig. 8 The flight profile of the TAEM phase based on X-37

3.4 Terminal area energy management (TAEM) guidance

The TAEM stage is designed to use up the kinetic and potential energy remaining at the end of the re-entry stage in preparation for a safe landing, as shown in Fig. 8. The core idea of TAEM segment planning is to smoothly transition from the re-entry segment's endpoint to the landing segment's beginning point according to the entry condition, terminal state, and constraint conditions. The difficulty lies in the extensive range of lateral and lateral maneuvers in the process, which puts forward higher requirements for guidance.

The trajectory tracking mainly realizes the guidance of the energy management segment. It is the same as the realization method of the climbing and orbit stages. However, the choice of control and state variables used for error feedback differs slightly. Zhang Henghao [120] used the heeling Angle as the control variable for lateral guidance, and the proportional guidance law was designed with the course Angle deviation feedback in the capture section. The reference velocity was calculated in the course calibration section according to the geometric characteristics of the calibrated cylinder, and the required heeling Angle was solved with the reference velocity. In longitudinal guidance, the Angle of attack is taken as the control variable. The nominal values of the Angle of attack and the trajectory inclination of the state variable are solved by the designed dynamic pressure-height profile and the tilt Angle instruction of lateral guidance. The guidance loop then uses trajectory inclination feedback to adjust the Angle of attack. Craig [121] proposed a method for calculating profile parameters: design the quadratic curve trajectory of undetermined parameters in the height-range profile and track the trajectory during guidance. Burchett [122] applied a fuzzy control strategy to achieve guidance, which can adapt to the coverage requirements of multiple constraints. Chi Zheng

[123] proposed a guidance law design method based on sliding mode control and conducted nominal state and Monte Carlo simulations.

3.5 Landing guidance

The return landing is the last phase of the flight profile. The return mode of horizontal landing significantly improves aerospace vehicles' reusable efficiency and cost-effectiveness ratio, which has broad application prospects and economic values. The whole reentry process is generally an unpowered flight. Aerodynamic layout design, thermal protection system, and advanced navigation guidance control technology are the keys to the development and design of the entire vehicle. An accurate and stable return landing is of great significance for flight safety and ground safety, as well as the reusability of the vehicle.

3.5.1 Research status of the trajectory design method

The landing phase guidance is mainly realized by trajectory tracking. While the tracked nominal trajectory can be designed and generated in both offline and online ways. However, the method to achieve trajectory tracking is consistent with other flight segments. As a result, a brief introduction to the trajectory design is presented before the guidance method.

In the work of She [124], the landing phase is divided into four subsegments: Steep glide, circular pull-up maneuver, the exponential transition phase, and slope glide. Based on this, Ding [125] designed the dynamic pressure-altitude profile according to the constraint conditions and obtained the corresponding ballistic dip-altitude profile. At the same time, the impact of landing mass, control surface allocation, and landing gear retraction on trajectory design were considered. Huang [126] proposed a path-planning method for an unpowered emergency approach and returned based on the Dubins curve, considering the engine failure situation. First, all feasible paths are constructed with Dubins' paths. To reduce the search scale of the feasible paths, several feasible paths with mappings between them are defined as an equivalence group, and the optimal search is performed in the equivalence group. To improve path design efficiency, Schierman [127] studied the generation technology of automatic landing trajectory and method to search the optimal path according to flight status. In essence, this method is not online trajectory generation but is based on the idea of a trajectory database instead. In the early stage, many offline simulations are carried out to build a trajectory database. The optimal trajectory profile corresponding to the current state is searched from the database according to the current flight state. In addition, each offline trajectory corresponds to a unique code, successfully avoiding the problem of considering trajectory design segments in the online process. Moreover, the trajectory generated by introducing disturbance factors into the offline database has the capability of disturbance resistance.

3.5.2 Research status of landing guidance

In the guidance sector, Peng [128] proposed PID (Proportion-Integration-Differentiation) guidance law based on altitude feedback in longitudinal guidance and two schemes for lateral guidance: PD guidance law based on side yaw and side yaw velocity feedback and PI control law based on side yaw and yaw Angle feedback. Proportional and integral terms were added to the side yaw, while proportional terms were only added to the yaw Angle. Yang Juntang [129] applied the LQR method, established the state-weighted and control-weighted matrices according to the dynamic model, and calculated the increment of control variables according to the feedback of small disturbance deviation. Schierman [130] studied the adaptive guidance method based on online trajectory search technology of offline database, established an online variable gain guidance loop, applied a neural network to identify the current state online, and adjusted the gain of the guidance loop. Cheng [131] proposed a real-time optimal control method using deep neural networks (DNN) to achieve accurate and robust soft landing of asteroids under the irregular gravity field. Five DNNS were developed using the approximate indirect method to learn the functional relationship between the state and the optimal action. A landing controller based on DNN was generated to generate the optimal control instruction according to the flight state.

3.5.3 State estimation

Extracting accurate information about the state of a control system, especially in the aircraft and robotics field, often requires state estimation as an effective strategy for noise reduction. The FIR-smoothing techniques in [132, 135] improve the estimation performance regarding observation data with time delay. The faulty signal disturbing the controller stability is also estimated based on the mean-field theory in [134, 139]. The methods in [133, 136–138] promote immunity to the disturbance using the Bayesian inference to depict the randomness of the unknown signals.

4 Development and prospect

4.1 Ascent phase

The combined dynamic-accelerated ascent stage of space vehicles has the following complex problems: first, the average acceleration in the climbing process is small, and the guidance error will continue accumulating in the atmospheric flight for a long time; Second, the flight constraints are strong. The combined power engine has strict constraints on the size of the flight Angle of attack, sideslip Angle, and its dynamic process. This is also manifested by the small push drag margin in the transonic process and the narrow flight state window in the engine mode transition. The fuel-equivalent ratio affects not only the engine performance but also the aerodynamic performance. The trim rudder may bring a large drag increment, reflected in the cross-coupling between the control variable and the flight state.

The current main research uses flight trajectory optimization and parameter planning theory to complete the flight trajectory design of the combined dynamic climb stage. Then it uses the nominal trajectory tracking method to achieve the guidance requirements of the combined dynamic climb stage.

In the follow-up research work, on the one hand, to better meet the requirements of engineering applications, flight strategy research and corresponding flight profile planning should be completed based on the flight mechanics characteristics of the combined power space vehicle during the climbing stage, aiming at the dynamics features such as takeoff at high Angle of attack, transonic push–drag modes, modal conversion traps, and wide-area aerodynamic/propulsion coupling. On the other hand, to further improve the guidance performance, we should gradually expand the adaptive guidance technology under thin atmosphere conditions and focus on solving the effect of introducing nonlinear characteristics such as aerodynamic and propulsion on the adaptive guidance solution efficiency.

4.2 Orbit-entry phase

The current mature iterative guidance technology can be applied to space vehicle rockets' dynamic orbit-entry stage to achieve the high-precision orbit-entry task under normal conditions. At the same time, since the orbit-entry stage has been removed from the maximum flight action pressure stage, the application of online trajectory optimization theory methods based on convex optimization also has potential engineering feasibility, which will further improve the guidance accuracy and performance.

4.3 Re-entry phase

In the re-entry phase, not only the constraints of dynamic pressure, overload, and heat flow brought by the requirements of dynamic thermal load should be considered but also the constraints of terminal speed, altitude, range, and control capability brought by the requirements of return field should be fully considered. This brings significant aerodynamics uncertainty and makes it more challenging to realize re-entry guidance with high accuracy. While the introduction of adaptive predictive correction guidance technology can cope with aerodynamic uncertainty and initial dispersion. The calculation efficiency has become a significant constraint on its progress because the predictive correction guidance should ensure the flight status prediction in every guidance period.

The adaptive predictive correction guidance technology can effectively solve the re-entry guidance problem with high precision under the condition of initial strolling error and aerodynamic uncertainty, which has been proved by the re-entry and return test of the new generation manned spacecraft test ship. However, a more critical step in predictive correction guidance is to predict the flight state of the re-entry terminal during each guidance cycle. Its computational efficiency is the bottleneck problem restricting the further improvement of adaptive re-entry guidance technology.

Introducing a deep learning model to significantly improve the computational efficiency of remaining range and landing position prediction and even solve the problem of rapid identification of aerodynamic parameters of lift vehicles during reentry will be a potential technical approach to improve the re-entry guidance performance further.

At the same time, introducing intelligent machine learning technology can provide possible solutions to problems such as mission change, vehicle failure, and online no-fly zone avoidance during re-entry guidance and improve the autonomous decision-making ability, trajectory guidance quality, and mission reliability of space vehicles during reentry.

4.4 Landing phase

In the process of return landing, the lift drag is relatively low. To maintain a slow glide state, the flight Angle of attack needs to be large, and the rudder deflection needs to be large. For a typical control layout scheme, a large control rudder deflection will significantly affect the lift drag performance of the aircraft, presenting outstanding non-minimum phase characteristics. Moreover, the landing process is an unpowered flight phase, which means higher flight quality and reliability.

The second sub-stage aircraft adopts the unpowered autonomous landing scheme. Once the landing fails, it cannot go around, which has high requirements for the quality and reliability of landing missions. Achieving high-precision autonomous landing under significantly non-minimum phase conditions must be further studied.

Due to the non-minimum phase characteristics of the second sub-stage landing, the deflection of the rudder will significantly affect the aerodynamic lift–drag characteristics and then change the flight speed/altitude through trajectory dynamics. The requirement of velocity and altitude guidance will generate additional Angle of attack instructions and generate new deflection of the rudder through the attitude control loop, which is shown as.

Trajectory dynamics and attitude dynamics are strongly coupled. Therefore, it is necessary to research the trajectory/attitude coordination control strategy combined with the dynamics characteristics of the two sub-stage aircraft to ensure the quality of the flight mission during landing.

The characteristics of a large expansion of flight envelope, multiple flight mission modes, and high requirement of autonomous reliability require higher flight mission quality and stronger robustness characteristics. However, some significant advances have been made in guidance technology. Combining the space vehicle's dynamics characteristics with the flight mission's requirements is necessary to improve the guidance performance further. In conclusion, the long-term research on the trajectory optimization problems of combined power vehicle under multiple modes and constraints have produced desirable solutions. The potential directions of further research involve introducing AI or customized solver to enhance calculation efficiency further.

5 Conclusion

The aerospace vehicle development and the critical problems of space vehicle guidance and control technology are reviewed and sorted out in this paper. Combined with the difficulties and problems existing in the current research, the follow-up development direction and ideas of the space vehicle guidance and control technology are then put forward. The multi-task, high maneuver, and changeable working modes bring many challenges, such as abrupt mission changes, external interference, internal uncertainties, fast time-varying parameter system instability, etc. As a result, in future research, more attention can be paid to emerging development fields like autonomous adaptive guidance, robust nonlinear control, advanced control algorithm, and high-precision intelligent autonomous navigation.

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Declarations

Conflict of interest The authors have not disclosed any competing interests.

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