Research on Guidance and Control Law Design of Decelerating Transition and Vertical Landing for a STOVL UAV

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Abstract. In this paper, an integrated design method for guidance and control laws for a short takeoff and vertical landing (STOVL) unmanned aerial vehicle (UAV) during decelerating transition and vertical landing phases under thrust vector control is studied. Based on the principle of time-scale separation, the outer-loop guidance law adopts an implicit dynamic inverse method to provide attainable overload vector control instructions for decelerating transition and vertical landing phases. Meanwhile, the inner-loop control law adopts an improved eigen-structure assignment method, which tracks guidance instructions and maintains a stable attitude. The attitude nozzles are joined to the attitude control with the dropping of dynamic pressure, thereby assisting aerodynamic surfaces to stabilize attitudes. Subsequently, the feasibility and effect of the control methods for a STOVL UAV during decelerating transition and vertical landing phases are verified by a 6-DOF flight simulation platform. The simulation results demonstrate that the integrated design method is beneficial for a quick evaluation of the overall scheme.

1. Introduction
Short Take-Off and Vertical Landing (STOVL) aircrafts have important applications in both military and civilian fields. Unmanned aerial vehicles (UAVs) with STOVL capabilities are the main developmental ambition of the next generation of unmanned aerial vehicles [1-2]. STOVL aircrafts have special flight dynamics and guidance control requirements for short take-off, acceleration and deceleration transitioning and subsequent vertical landing phase of flight compared to conventional take-off and landing procedures for fixed-wing aircraft and helicopters. With particular regard to the process of a decelerating transition, as the flight speed proceeds to drop to zero, the aerodynamic force is weakened, which causes the aircraft to lose lift force, following which the dynamic stability is reduced and the efficiency of aerodynamic control surfaces are decreased. Therefore, it is necessary to introduce the engine thrust vector control to compensate for the lift force, wherein the combined control of attitude nozzles and aerodynamic surfaces can ensure the stability of the attitude control of the aircraft. During the vertical landing process, the ground effect has a serious impact on the downward-jet of the engine, and the flight dynamics exhibit a high degree of nonlinear coupling characteristics. Simultaneously, for a STOVL UAV, which must possess the capacity for autonomous
flight, it is necessary to design an outer-loop guidance law and an inner-loop control augmentation system, which manned aircraft do not require. To complete autonomous landing missions and achieve the best comprehensive flight performance, the coupling of inner and outer loops should be avoided.

The nonlinear dynamic inversion control method is one of the important technical means with which to design aircraft control laws. Feedback linearization technology is used to solve the inverse system containing the nonlinear dynamics and kinematics equations in order to obtain the virtual closed-loop pseudo-linear system. This method can be applied to the guidance law, wherein the tracking errors can be converted into the input instructions of the inner loop control law to ensure that the track deviations are linearly convergent. However, the processes through which the kinematic relationships and the dynamic characteristic distributions of the navigation system are solved must be carried out separately and seem very complex [3-4]. In the design of the inner loop control law, the eigen-structure assignment method is one of the most effective technical means with which to control multiple-input multiple-output (MIMO) systems of an aircraft. Smith [5] resolved the problem of stability and modal coupling within harrier STOVL multi-input and multi-output dynamic systems in a transitional state by distributing the left and right eigenvectors of the system simultaneously. White [6] introduced the polynomial eigen-structure technique for the design of a system dynamic compensator, which decouples the system modal and improves the tracking flight-path angle performance of the harrier STOVL aircraft. However, the simple eigen-structure assignment method cannot directly consider the robustness of the controlled object model uncertainty.

This paper considers the technical characteristics of a thrust vector STOVL UAV in order to investigate a fast integrated design method for the autonomous guidance and control law in the process of a decelerating transition toward a vertical landing, as well as to provide an evaluation of a closed-loop simulation for the overall design of the control configured vehicle. The implicit dynamic inverse method is used to design the guidance law, which converts the tracking deviation into the attitude and overload vector instructions. This method is based on the time-scale separation of the outer-loop and inner-loop and neglects the dynamic characteristics of the inner-loop, thus simplifying the outer-loop guidance law dynamic object into a standard second-order system. The natural frequency and damping characteristics of the second-order closed-loop guidance system are distributed using a direct collocation method. Compared with the conventional nonlinear dynamic inverse method, it is simpler to solve the inverse with this method, and it can be applied to track curvilinear flight paths. The inner loop control law adopts the improved eigen-structure assignment method with an integrator. By introducing the integrating link, a decoupling of the characteristic modes is achieved, whereby the robust performance of the control system is improved and the tracking error is reduced. The design process is simple and suitable for the rapid evaluation of the overall scheme. Based on the comprehensive design of the outer-loop guidance law and the inner-loop control law, a flight simulation of a STOVL UAV with thrust vector control is carried out, and the effectiveness of the overall design scheme is evaluated. Simultaneously, the feasibility of the rapid integrated design method is verified.

2. Thrust Vector Scheme of STOVL UAV

Generally, a STOVL UAV applies thrust vector technology to provide the force balance and attitude maneuverability during a slow flight state in consideration of aerodynamic inefficiencies. The engine contains two front lift vector nozzles on the right and left sides as well as one primary vector nozzle in the rear, all of which are capable of spinning freely downward to a maximum of 98° from the horizontal symmetric plane of the aircraft (i.e., they can spin slightly forward for deceleration). These lift-vector nozzles chiefly provide the rise power for short take-off, transition and vertical descent phases, as well as the balancing capabilities for static pitching (by adjusting the front and rear thrust vector differentials) and rolling (the left and right thrust vector differentials). By bleeding air from the engine turbine, the power system also provides a pair of pitch attitude control nozzles mounted at the nose and the tail, a pair of rolling attitude nozzles mounted on the left and right wings and a pair of yaw attitude nozzles mounted at the tail. Limited three-axis control moments are provided at low
speed to control and stabilize the attitudes [7].

The aerodynamic configuration of the STOVL UAV with a thrust vector scheme adopts a conventional layout with ailerons, elevator and rudder, and also possesses trailing edge flaps.

3. Approximate Dynamic Inverse Method for the Outer Loop Guidance Law

The aim of the guidance law of an aircraft is to calculate control commands based on track deviations such that the aircraft converges to a predetermined flight path within a predetermined mode. Fig. 1 only shows the lateral guidance as an example to illustrate the design method because of the article length limitation [7].

The guidance law and its controlled object can be approximated as a linear system (Fig. 2). Consequently, the closed-loop transfer functions for the heading deviation and track deviation can be written separately.

![Figure 1. Lateral navigation and guidance schematic diagram](image1)

![Figure 2. Lateral navigation and guidance structured flowchart](image2)

4. Design Method of the Inner Loop Control Law

The approach that is employed to configure the eigenvalues and eigenvectors of a system using state feedback or output feedback is called eigen-structure assignment [8-10]. Compared with the eigenvalue configuration method, the eigen-structure assignment technique is capable of simultaneously achieving the predetermined dynamic performance of system in addition to realizing the decoupling between modes [11].

The eigen-structure assignment method requires a high accuracy for the flight dynamics model, and there is no guarantee of robustness when modeling uncertainties and perturbations. By introducing the integral link into the eigen-structure assignment technique, a decoupling of the modes is realized, and the robustness of the control system is improved concordant with a reduction in the tracking error. A
structured flowchart is shown in Fig. 3.

Firstly the 6-DOF flight dynamics model of STOVL UAV was initially trimmed to extract the linearization model, following which the feedback control system was designed. The inner loop control law design of an aerodynamic surface for a STOVL UAV with a thrust vector scheme adopts an eigen-structure assignment using the integral method meanwhile taking into account the dynamic characteristics of actuators. Considering the longitudinal overload control as an example, the state variables of state space equation are \( X = [u \ w \ q \ \theta] \), which can be extended to \( \dot{X} = [u \ w \ q \ \theta \ \Delta \delta_e \ \delta_e] \), three state variables are added. The integral link is mainly to increase the robustness of the system, and the actuator dynamic link is mainly to consider the dynamic characteristics of the actuator in the process of controller design.

![Structured flowchart](image)

**Figure 3. Improved eigen-structure assignment method structured flowchart**

5. **Flight Simulation Verification**

The autonomous flight simulation of a STOVL UAV was conducted using the established flight dynamic model and the designed guidance and control system.

Upon completion of the mission, the STOVL UAV initiates its return, performing a deceleration transition and a vertical landing. In the beginning phase of changing from a cruise state into a deceleration transition state, the airspeed of the aircraft is approximately 230 km/h, the lateral displacement difference of the current location and vertical landing point is approximately 1000 m, the lateral position difference is approximately 0 m, and the current height of the aircraft is roughly 48.6 m. During the process of the deceleration transition, the height of the aircraft is kept unchanged, the lateral displacement difference is expected to be zero, and the longitudinal position difference relative to the vertical landing point is gradually reduced. When the airspeed is less than 80 km/h, it shifts into a vertical landing phase, and the longitudinal displacement difference is gradually narrowed according to outer-loop guidance instructions simultaneous with a reduction in ground speed. Upon arrival to the airspace above the designated vertical landing point, a vertical landing is initiated at a specified speed.

The aforementioned designed guidance law and control law are used to simulate the deceleration transition and vertical landing process of the STOVL UAV. The wind speed is 5 m/sec within the simulation when gust disturbances are considered. The vertical landing speed is set at 1.0 m/sec. The full simulation process, starting from a deceleration transition to a vertical landing, is as follows:

- 0.0 sec: starts deceleration transition;
- 25.0 sec: transfer from the transition phase to a vertical landing;
- 68.0 sec: successful completion of landing.

The longitudinal displacement difference during the deceleration transition and vertical landing is shown in Fig. 4. The lateral displacement difference is shown in Fig. 5, while Fig. 6 illustrates the height change. Fig. 7 shows the vertical landing rate, the horizontal ground speed is shown in Fig. 8, and Fig. 9 displays the airspeed change.

From the simulation results, it is apparent that the variation of the dynamic characteristics of the
aircraft is more severe due to the deflection of the vectoring nozzle from the horizontal position to the maximum angle (98°) at the beginning of the transition. The flight height and the attitude angle are also characterized by a certain deviation. At the time of landing upon the ground, the aircraft attitude, etc., will exhibit a substantial change when impacting the ground at a certain speed.

From the height variation, it can be observed that the flight height during the deceleration transition phase is maintained at roughly 50 m; when entering the vertical landing phase, the flight height gradually decreases. An indication that the aircraft has reached the landing point airspace is achieved when the horizontal ground speed and longitudinal displacement difference are reduced to zero.

6. Conclusions
According to the deceleration transition and vertical landing requirements of a STOVL UAV with a
thrust vector, a reasonable control strategy is adopted to realize a deceleration transition and vertical landing. In the control distribution of an aerodynamic surface and thrust vector, only a relatively simple allocation is conducted. The methods to optimize the aerodynamic surface, thrust vector and fault tolerance distribution require further study.

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