Research on UAV Flight Test Technology Based on Embedded Commands

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Abstract. This paper presents the current situation that the pilot’s manual operation method can’t fully meet the requirements of UAV flight test. To solve the problem, a UAV flight test technology based on embedded command is proposed. By analysing the verification contents and assessment methods of UAV flight test, the typical actions in UAV flight test are extracted, the embedded command modules are designed, and the embedded command flight test method is formulated. The flight test results show that compared with the manual operation method, the embedded command flight test technology can alleviate pilot’s operation burden, reduce the flight test risks and improve the flight test efficiency.

1. Introduction

Generally speaking, the UAV system is composed of UAV platform, ground control station, data link system and ground support system. Compared with the manned aerial vehicle flight test, the UAV flight test has both similarities and uniqueness. The UAV platform as the basis and key component of UAV system, evaluating its function and performance by flight test, is an effective means to verify whether the UAV system meets the expected requirements [1]. During the flight test of UAV system, pilot's manual operation relies on the ground control station and data link system. As the pilot is separated from the aircraft platform during the flight, he couldn’t sense the flight status. In addition, because of the existence of link time delay, the traditional method of manned aircraft flight test has some limitations and deficiencies when applied to the UAV flight test [2].

Based on requirements of UAV platform flight test, this paper sorts out the UAV platform flight test verification project and establishes the cell library for the UAV typical flight test actions. By analysing the characteristics of UAV flight control system and the limitations of traditional manual stick-rudder control method, a flight control method based on typical flight test action commands is proposed. This method designs embedded commands for typical flight test actions, and proposes a verification scheme which is based on the UAV flight control system for typical flight test actions. The flight test results show that the method has good effect on the execution and completion of flight test actions when compared with the traditional manual stick-rudder control method.

2. Status of embedded commands flight test

From 2001 to 2018, the U.S. Department of Defense has issued 8 versions of unmanned systems integrated roadmap, which are used to guide the overall development of the U.S. military in the field of UAV system [3]. During this period, Great progress has been made from the basic technology to the demonstration project of UAV. Among which the most famous ones are the HALE (high altitude long endurance) UAV represented by Global Hawk and the MALE (middle altitude long endurance) UAV.
represented by predator [4-5]. Compared with the rapid development of UAV technology, the relative research on flight test methods and assessment standards is slower; most of them still refer to the methods of manned aircraft, there are deficiencies and defects which can’t meet the requirements of UAV flight test [6].

According to the current design ideas of UAV system, there are great differences in system configuration between UAV and manned aircraft. During the flight test of UAV system, pilot’s manual operation relies on the ground control station and date link system, as the pilot is separated from the aircraft platform, he couldn’t sense the flight status, and because of the existence of link time delay, the pilot’s manual operation quality is not high, the effect of flight data is also bad. Some actions even need to be done by repeating the flight test many times, which will lead to low test efficiency and increase the test cost [7]. Meanwhile, due to the complexity of UAV system, its reliability is relatively fragile, so the flight safety depends on the design of flight test method. When the pilot’s manual operation intervenes in the control, it will increase unnecessary risks. Therefore, it is of great significance to complete the execution and operation of typical flight test actions by embedded instructions in UAV platform flight test. The United States has carried out the embedded command research in many UAV models. Early example is the in-flight stability analysis techniques in X-29A vehicle based on the embedded command [8-9]. More recently, in the X-43A and NF-15B vehicle flight test, the automated injection of multisine excitations was used to simultaneously characterize the stability of multiple axes with postflight analysis [10-11], in the X-48B aircraft flight test, a set of inner loop control system based on dynamic inverse was developed, and multiple exciting actions were embedded [12].

3. Establish the cell library of typical flight test actions
Like manned aircraft, the flight test assessment scope of UAV platform can be also divided into flight performance test, flight quality test, and flight control system test, based on these three specialties, this paper sorts out the flight test verification items and typical flight test actions.

For the flight performance specialty, the flight test assessment items mainly include airspeed system calibration, take-off performance, climbing performance, practical ceiling, maximum level flight speed, minimum level flight speed, endurance performance, glide performance, manoeuvrability, hover performance, landing performance, mission performance, etc. The typical flight test action cells that can be decomposed are stable level flight, level flight acceleration, level flight deceleration, fast climb, slow climb, fast glide, slow glide, stable turn left, stable turn right, stable hover, constant heading angle flight, constant track flight, dive acceleration, altitude remote adjustment control, speed remote adjustment control, etc.

For the flight quality specialty, the flight test assessment items mainly include longitudinal static stability, longitudinal dynamic stability, lateral-directional static stability, lateral-directional dynamic stability, transient characteristics, residual oscillation, artificial simulated landing, etc. The typical flight test action cells that can be decomposed are stable level flight, level flight acceleration, level flight deceleration, level flight deceleration, fast climb, slow climb, fast glide, slow
glide, stable turn left, stable turn right, stable hover, constant heading angle flight, constant track flight, dive acceleration, longitudinal pulse, longitudinal multiple pulse, longitudinal 3211, longitudinal sweep frequency, longitudinal step, lateral step, lateral sweep frequency, course step, coordinated sideslip, lateral multiple pulse, course multiple pulse, lateral-directional combined multiple pulse, altitude remote adjustment control, speed remote adjustment control, side deviation remote adjustment control, constant roll angle flight, constant pitch angle flight, etc.

4. Design of embedded commands

4.1. Classification and control strategy design of UAV typical flight test actions

UAV uses embedded command method for the purpose of achieving the action excitation in a standard, normative and effective way, obtaining the high-quality test data, and ensuring the controllability of UAV flight state.

In the process of typical flight test action commands design, the action cells in the cell library firstly need to be classified according to the action types. In this paper, the typical flight test actions are divided into four types: level flight acceleration and deceleration commands, remote control commands, model excitation commands and attitude control commands.

4.1.1. Level flight acceleration and deceleration commands. The level flight acceleration and deceleration commands include level flight acceleration command and level flight deceleration command. For the level flight acceleration command, the control strategy is to switch the throttle to the open-loop control state, then push the throttle from the current position to the rated state quickly, the calibrated airspeed will increase to the specified value, finally turn into the speed closed-loop control, and then switch the throttle to closed-loop state after a set time. For the level flight deceleration command, the control strategy is to switch the throttle to the open-loop control state, then push the throttle from the current position back to the idle state quickly, the calibrated airspeed will decrease to the specified value, finally turn into the speed closed-loop control, and then switch the throttle to closed-loop state after a set time.

4.1.2. Remote control commands. The remote control commands include altitude remote adjustment control command, speed remote adjustment control command and side deviation remote adjustment control command. For the altitude remote adjustment control command, the control strategy is to record the altitude value at the current moment, then on the basis of the flight altitude limit conditions of UAV, add an increment as the expected value, and finally switch to the altitude remote adjustment control command. For the speed remote adjustment control command, the control strategy is to record the speed value at the current moment, then on the basis of the flight speed limit conditions of UAV, add an increment as the expected value, and finally switch to the speed remote adjustment control command. For the side deviation remote adjustment control command, the control strategy is to record the side deviation value at the current moment, then on the basis of the flight side deviation limit conditions of UAV, add an increment as the expected value, and finally switch to the side deviation remote adjustment control command.

4.1.3. Model excitation commands. The model excitation commands include longitudinal step command, lateral step command, course step command, longitudinal pulse command, longitudinal multiple pulse command, course multiple pulse command, longitudinal 3211 command, longitudinal sweep frequency command, lateral sweep frequency command and lateral-directional combined multiple pulse command. For the longitudinal step command, the control strategy is to disconnect the normal overload circuit in the flight control system, and inject a rectangular wave signal. For the lateral step command, the control strategy is to disconnect the roll angle rate circuit in the flight control system, and inject a rectangular wave signal. For the course step command, the control strategy is to disconnect the sideslip angle circuit in the flight
control system, and inject a rectangular wave signal. For the longitudinal multiple pulse command, the control strategy is to disconnect the normal overload circuit and inject a longitudinal multiple pulse signal. For the lateral-directional combined multiple pulse command, the control strategy is to disconnect the sideslip angle circuit and the roll angle rate circuit, and inject a lateral-directional combined multiple pulse signal. The operation principle of other pulse commands is basically the same, which is not listed.

4.1.4. Attitude control commands. The attitude control commands include fast climb, slow climb, fast glide, slow glide, stable turn left, stable turn right, stable hover, dive acceleration, stable level flight, coordinated sideslip, constant roll angle flight, constant pitch angle flight, constant heading angle flight, constant track flight, etc. The control strategy can be divided into four categories: altitude hold control, roll angle control, pitch angle control, and heading control. For the altitude hold control, the control strategy is to record the altitude value at the current moment, then on the basis of the flight altitude limit conditions of UAV, add an increment as the expected altitude command value, switch to the altitude hold mode, after a set time, and finally switch back to normal status. For the roll angle control, the control strategy is to record the roll angle value at the current moment, then on the basis of the flight roll angle limit conditions of UAV, add an increment as the expected roll angle command value, switch to the roll angle hold mode, after a set time, and finally switch back to normal status. For the pitch angle control, the control strategy is to record the pitch angle value at the current moment, then on the basis of the flight pitch angle limit conditions of UAV, add an increment as the expected pitch angle command value, switch to the pitch angle hold mode, after a set time, and finally switch back to normal status. For the heading angle control, the control strategy is to record the heading angle value at the current moment, then on the basis of the flight heading angle limit conditions of UAV, add an increment as the expected heading angle command value, switch to the heading angle hold mode, after a set time, and finally switch back to normal status.

4.2. Implementation principle of embedded command

In order to simulate the manual operation by embedded command control method, it is necessary to add the flight test action command module before flight control system. Figure 1 shows the schematic diagram of embedded command implementation.

![Figure 1. Schematic diagram of embedded command implementation](image-url)

During the implementation, the pilot initiates the action command in the ground control station, and the command is transmitted to the date link airborne terminal through the data link, which triggers the embedded command module at front of the flight control system. After the embedded command is processed by the flight control system, the steering surface deflection command is output to the control
surface controller. On the one hand, the state response of the UAV is transmitted to the ground control station through the UAV's own data link which is used for pilot monitoring; On the other hand, the state response can also be transmitted to the ground monitoring system for technicians to observe through the additional telemetry link. The ground monitoring system and the ground control station can be connected through communication equipment.

According to the control characteristics of UAV system, the design of embedded command modules needs to be achieved from the three aspects: speed control design, attitude control design and trajectory control design. For the speed control design, it is based on the automatic throttle control loop. In the design of speed related commands (such as level flight acceleration and deceleration commands), the throttle is in the open-loop state first, and the desired speed is taken as the command value to control the engine throttle. When the speed reaches the specified value, it turns to the speed closed-loop control state. After a set time, switch back to the throttle closed-loop status. The speed control loop diagram is shown in Figure 2.

For the attitude control design, it is divided into pitch hold control, roll angle hold control, and heading angle hold control. When designing the UAV attitude control command, the desired attitude is used as the command value, based on the current attitude, the UAV automatically calculates the attitude change and controls the UAV to respond to the input command. The pitch hold control is used as an inner loop of longitudinal control, which improves the damping ratio and longitudinal stability of UAV. When the throttle is constant, the pitch angle of UAV is held by adjusting the elevator. The pitch hold control loop is shown in Figure 3 (a). The roll angle hold control is the same as that of pitch hold control. The angular rate compensation is used as the inner loop controller to feedback the roll angle rate, so as to increase the damping and improve the control performance. The outer loop of roll angle hold control is angular position feedback. The roll angle of UAV is measured by vertical gyro sensor, forming a closed loop for series control. The roll angle hold control loop is shown in Figure 3 (b). The control law of heading angle hold control takes the lateral roll angle hold control loop as the inner loop; the heading angle hold control loop is shown in Figure 3 (c).
For the trajectory control, it mainly includes altitude hold control and lateral deviation control. When designing the command, the desired altitude or desired lateral deviation is taken as the command input, based on the current altitude or lateral deviation, the UAV automatically calculates the change of altitude or lateral deviation and controls the UAV to respond to the input command. As a part of longitudinal control, the altitude hold control loop of UAV takes the pitch angle hold control loop as inner loop, and designs with altitude change rate and altitude variation as feedback. The altitude hold control loop is shown in Figure 4 (a). The lateral deviation control loop uses the lateral roll angle hold control loop as the inner loop, as is shown in Figure 4(b).

5. Test verification of embedded commands
After the design of the embedded commands is completed, in order to ensure the safety of the flight test, it is necessary to carry out sufficient ground tests before the flight test. The verification contents of the ground tests mainly include checking the rationality of embedded commands design, checking the cross-linking matching between embedded commands and flight control system, preliminarily designing the scope of excitation signals, carrying out the function inspection and the fault simulation drill of embedded commands, etc.

In this paper, an UAV platform is selected for the embedded command flight test verification. In the verification, the flight test actions are carried out by manual operation method and embedded command method respectively. Due to the space limitations, four typical flight test results are given here, as shown in Figure 5 to fig Figure 8. The selected typical flight test actions include level flight acceleration, longitudinal multiple pulse, lateral-directional combined multiple pulse and stable hover.
As can be seen from Figure 5 to Figure 8, for the level flight acceleration action, the control principle of manual operation method and embedded command method are the same which demands to push the throttle stick deflection to the rated state quickly, so the throttle stick deflection and the flight speed change trend of the two control methods are basically the same. However, it can also be seen that the embedded command method for the altitude control is obviously better than manual operation method; for the longitudinal multiple pulse action and lateral-directional combined multiple pulse action, the results show that the control effect of embedded command method on rudder deviation is significantly higher than that of manual operation control, the changing effect of attitude angle and attitude angle rate induced by embedded command method is significantly higher than that of manual operation method, and the data of flight test is more conducive to the flight quality evaluation; for the stable hover action, the embedded command method is also significantly better than the manual operation method in the altitude, speed and roll angle control, which is more conducive to the completion of UAV flight test tasks.

6. Conclusion
In view of the limitations of manual operation method, this paper proposes the embedded command technology based on typical flight test actions of UAV. By sorting out the UAV platform flight test items, a typical flight test action cell library is established, and the embedded command control modules and the flight test verification schemes are designed. The flight test results show that compared with the manual operation method, the embedded command method can alleviate pilot’s operating burden, reduce the flight test risks and improve the flight test efficiency.

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