33RD CONGRESS
OF THE INTERNATIONAL COUNCIL
OF THE AERONAUTICAL SCIENCES
STOCKHOLM, SWEDEN, 4-9 SEPTEMBER, 2022

FLIGHT VERIFICATION OF AUTOMATIC TRANSITION FOR QUAD TILT WING SMALL UAV

Koji Muraoka [1] & Masayuki Sato [1]

[1] Japan Aerospace Exploration Agency

Abstract

This paper deals with the automatic transition methodologies for a QTW (Quad Tilt Wing) small VTOL UAV, which features tandem tilt wings with propellers mounted at the mid-span of each wing. The automatic transition algorithm was designed aiming to implement full automatic transition flight capabilities to the existing QTW auto-flight system. The algorithm changes tilt angle automatically to maintain the aircraft within the safe flight envelope while it also simultaneously coordinates navigation and guidance controllers, which is the main contribution of this paper. The algorithm was installed to the QTW UAV platform and a full transition flight test including vertical take-off, accelerating transition, cruise, decelerating transition and hover landing was successfully accomplished.

Keywords: VTOL, UAV, Tilt Wing Aircraft, Transition Flight, Flight Test

1. Introduction

VTOL (Vertical Take Off and Landing) and automation are key techniques for the revolution of air mobility and future business models [1]. Recently, various types of eVTOL aircraft and VTOL UAS (Unmanned Aircraft System) are proposed [1,2], and a lot of research and development effort are intensively conducted. Among those VTOL aircraft transformable configuration, which features tilt propellers, tilt wings, and so on, generally have both VTOL and high-speed cruise capabilities. One of the issues to make such aircraft fly safely is to provide effective means for safe transition flight from vertical hovering to horizontal cruise and *vice versa*.

As one of the research programs in JAXA (Japan Aerospace Exploration Agency) to advance air mobility system [3], the authors have been conducting the research on VTOL system design technologies focusing on QTW (Quad Tilt Wing) VTOL aircraft in sUAS (small UAS) domain. QTW features tandem tilt wings with propellers mounted at the leading edges in the mid-span of each wing. The QTW configuration has neither additional propulsion devices such as vertical lift propellers nor tail rotors which are used only in hovering phase, which well demonstrates the effectiveness of the QTW configuration. The QTW configuration has an advantage in cruise performance due to the removal of additionally implemented hovering devices (such as tail rotors), and also has slow and middle speed capabilities as well as super-short take off capabilities which cannot be realized by multi-copter drones.

We have already developed auto-flight controllers which allow programmed navigation flight at all pre-defined wing tilt angles from 90 (deg) to 0 (deg) [5]. The controller has enabled us to have automatic flight beyond pilot's visual line of sight, however, the transition needs to be completed by a remote pilot within his/her visual line of sight before engaging auto-navigation mode. To conduct transition, a pilot needs to change wing tilt angles while applying attitude and throttle commands to maintain fight speed and flight path. These tasks are so complicated and a well-trained pilot is always required for flight. More efficient fight would be possible if these tasks are simplified or automated.

The purpose of the present research is to address these control difficulties by developing automatic transition algorithm and to implement fully automated transition flight capabilities to the QTW UAV.

Hartmann et al. [4] designed unified velocity control and flight state transition controller for a twin-propeller tilt wing UAV. The controller concept was demonstrated using a small UAV demonstrator. The controller used wing tilt angle not as the configuration device but as the control device to change airspeed. The speed change was performed while pitch attitude was maintained by another control devices such as the tail rotor and the elevator. Reference [5] and [6] provide control concept of another tilt-wing aircraft, however no information on detailed transition mechanics were given.
Since the tilt wing change comes with transition motion as well as significant change of the flight characteristics, the QTW's wing tilt change was treated not as a control device but as a configuration parameter. In the present research, the flight algorithm is designed to change tilt angle and to maintain the aircraft within the safe flight envelope coordinating with existing auto-flight system (automatic navigation mode).
In the following chapters, we will firstly describe the overview of the QTW VTOL UAV platform. Then, we will explain the design result of the auto-transition algorithm, and finally show flight test results and discussions on the results.

2. QTW VTOL UAV Platform

2.1 QTW UAV Flight Control Architecture

Figure 1 shows the QTW VTOL small electric UAV named "FWD02" which is developed as a technology demonstration platform for potential civil UAV missions [6]. Full transition flight and automatic route navigation function in airplane mode have already been demonstrated using FWD02. Figure 2 depicts the architecture of the existing auto-flight control loop. The loop comprises cascaded controllers of PFCS, CAS, Guidance, and Navigation Controllers, whose functions are summarized below.

- PFCS (Primary Flight Control System): PFCS changes the effectiveness of control devices according to the wing tilt angle. In helicopter mode (tilt angle is set 90 (deg)), the vehicle is controlled in pitch and roll via differential thrust, and yaw is controlled via flaperons attached with the front and rear wings using the propeller slipstream. In airplane mode (tilt angle is set 0 (deg)), the vehicle is controlled in pitch via flaperons, and in yaw via rudder. Thus, control device effectiveness is altered according to the wing tilt angle. Stability is augmented using pitch rate, roll rate and yaw rate feedback controllers.

Dimension	Length 1.7m Span 2.3m
Weight	MTOW 25kg Payload 2kg
Propulsion	Electric Motor (Fixed Pitch Propeller)
Onboard System	Flight Control Computer, Datalink, etc.
Sensors	Airdata, GPS/INS, RPM, etc.

Figure 1 – QTW VTOL sUAV "FWD02"

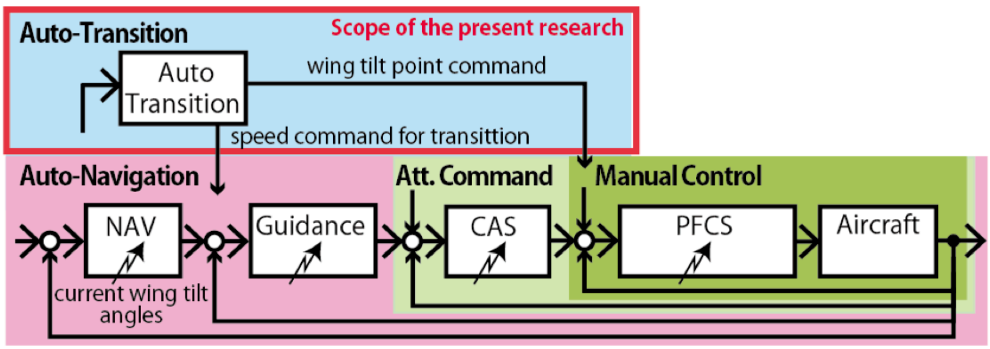


Figure 2 – Auto-flight control loop

- CAS (Control Augmentation System): CAS controls pitch and roll attitude by generating pitch stick and roll stick commands, respectively, to the PFCS. Attitude commands are provided either from pilot's stick inputs or guidance controller.
- Guidance Controller: Guidance controller maintains vehicle altitude (flight path), airspeed, heading etc. to track commands from the navigation controller. It generates pitch attitude, roll attitude, yaw stick and throttle commands to CAS controller by changing control strategies from "back side of power curve" technique to "front side" technique according to the wing tilt angle.
- Navigation (Programmed Flight): Navigation controller generates altitude, airspeed and course commands to the guidance loop to follow programmed flight path. The programmed flight path is defined by a set of way points, each of which has latitude, longitude and altitude command information as well as airspeed command information.

2.2 QTW UAV Flight Operations

Figure 3 shows the concept of flight operations using the existing flight control loops. Remote pilot commences vertical takeoff by putting commands to CAS control loop through the RC transmitter, and conducts accelerated transition by setting tilt angle position stepwise through the RC transmitter. After the QTW UAV configuration becomes cruise mode (i.e. zero wing tilt angle at cruise speed), the remote pilot engages auto-flight mode to start automatic navigation flight. GCS (Ground Control Station) operator takes over the responsibility of the flight and monitors the status of flight/aircraft conditions through the console display. When the vehicle returns around the base and comes into VLOS (Visual Line-Of-Sight) area, the remote pilot again takes over the flight control by changing control mode to CAS mode and perform decelerated transition through RC transmitter.
Since the existing controller requires manual selection of the tilt angle setting both in departure and approach phases, a well-trained remote pilot is required for flight. Also, it is difficult to perform transition beyond VLOS.
To overcome these operational difficulties, automatic transition algorithm for the QTW is designed in the next chapter.

3. Auto-Transition Algorithm Design

3.1 Design Requirements

This chapter summarizes the design of the auto-transition algorithm. Figure 4 depicts the safe flight envelope of the "FWD-02" QTW created by the analysis of its flight characteristics [7]. The flight envelope defines airspeed limits at any wing tilt angles. Safe transition could be performed safely by changing wing tilt angles while airspeed is maintained within the limits. A set of discrete wing tilt

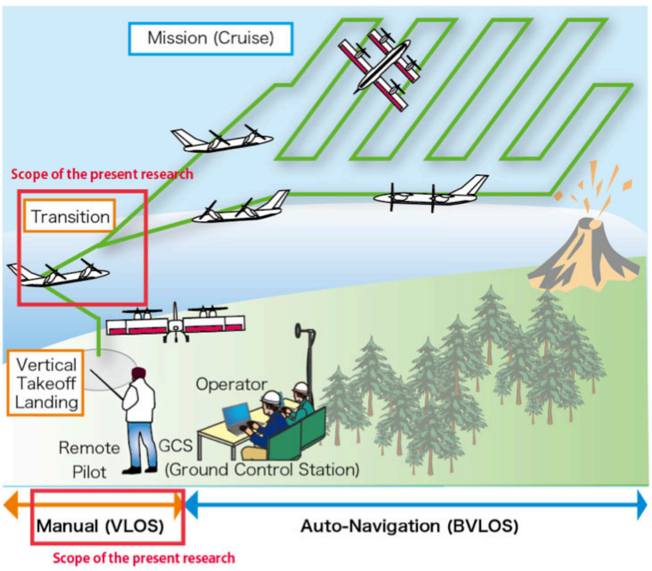


Figure 3 – Flight Operations (Concept Image)

angles (seven points) have already been defined as nominal tilt schedule so that a remote pilot can conduct manual transition by selecting a certain wing tilt angle from the set of pre-defined wing tilt angles.

To remove these tasks, we design the auto-transition algorithm. The design requirements are defined as:

1) It selects proper tilt angle command to maintain an arbitrarily set airspeed command.
2) It drives wing tilt angles to conduct accelerated or decelerated transition.
3) During both transition and steady flight, it prevents the deviation from the safe flight envelope shown in Figure 4.
4) Behavior of the auto-transition algorithm is consistent with the understanding of human GCS operators and of remote pilots so that they could take over the control in any case.

Since wing tilt angles are designated not as control surfaces but configuration parameters for the flight, the auto-transition algorithm is designed to change wing tilt angles stepwise as a human pilot does.

3.2 Tilt Scheduler

Figure 5 depicts the block diagram of the auto-transition algorithm designed in the present research. As the trigger input for the auto-tilt function, we select the target airspeed command which is provided either by auto-navigation loop or by a GCS operator's intervention. In both cases, the target airspeed command is interpreted not as a status parameter but as an intention to do acceleration or deceleration.

A target tilt angle could be determined directly using the flight envelope chart by the target airspeed

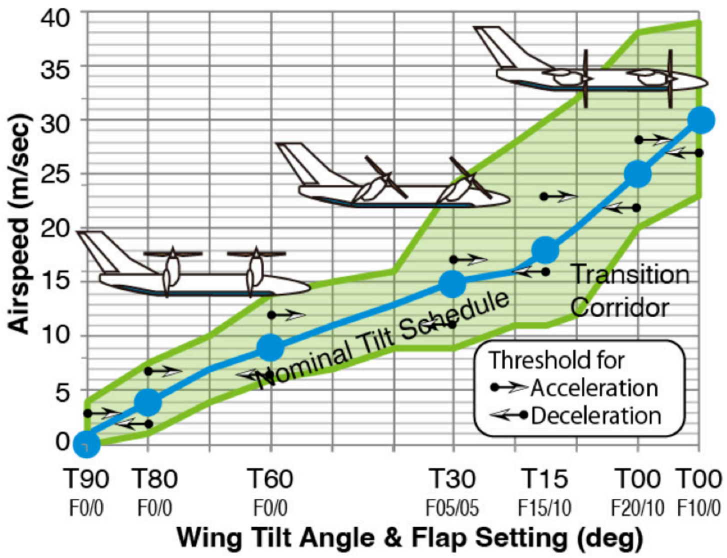


Figure 4 – Flight envelope of the QTW (Transition Corridor)

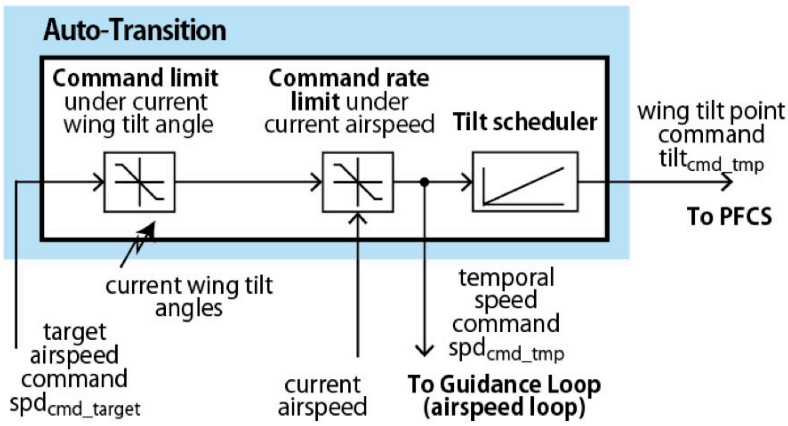


Figure 5 – Algorithm of the Auto-Transition

(Figure 4). However, these target tilt angle and the target speed should not be applied immediately to the inner loop controllers during the flight. The reason is given below. If the target airspeed command which is far from the current airspeed is applied, the speed control loop would try to control the aircraft to attain the command speed before the wing tilt angle reaches its target, which might cause the deviation from the safe flight envelope. Therefore, the auto-transition algorithm is designed to generate a temporally set airspeed command to make moderate acceleration or deceleration, and to update wing tilt angle command after the actual airspeed is sufficiently accelerated (or decelerated) to conduct the configuration change.

In the algorithm, the target airspeed command is revised through the command limiter and the command rate limiter. The command limiter is firstly applied so that the target airspeed does not exceed the limit of airspeed under the current wing tilt angle, then the revised target airspeed command go through the command rate limiter to prevent excessive acceleration or deceleration from the current airspeed. Then, the temporally set airspeed command is applied to the airspeed control loop.

The tilt scheduler selects the target wing tilt angle command and determines the timing to update the command by checking the temporally set airspeed command. Since each of adjoining wing tilt angles in the transition corridor (Figure 4) overlaps the designated preferable airspeeds, wing tilt angle can be changed at such airspeeds. QTW can thus change wing tilt angles staying within the safe flight envelope. When the temporally set airspeed command goes over or goes under the pre-defined threshold of the airspeed, the tilt scheduler updates the commands at the next wing tilt angle and physically drives the actual wing tilt angles. These sequences are repeated until the actual airspeed reaches to the target airspeed.

4. Flight Test Verification

4.1 Flight Test

Flight test was carried out to examine the functionality and the transition performance of the algorithm in the previous section. To verify the auto-transition algorithm, navigation flight plan path comprising a set of waypoints was prepared. Each waypoint contains three dimensional position data (latitude, longitude and target altitude), target airspeed. Target airspeed in each waypoint was designated to make acceleration and deceleration.

4.2 Results

Figure 6 shows the flight test results of the auto-transition from hovering taxi at 80 degrees of wing tilt angle to cruise at zero wing tilt angle. After takeoff controlled by a remote pilot using CAS mode, auto-navigation mode with the auto-transition algorithm was engaged, and the control was taken over by a GCS operator. Automatic transition flight was completed along with the flight plan path. In the transition flight, the target airspeed commands were created from the flight plan to go through the destination waypoints at the designated airspeed. After the deceleration, the aircraft landed vertically using the automatic hover and landing mode.

4.3 Discussions

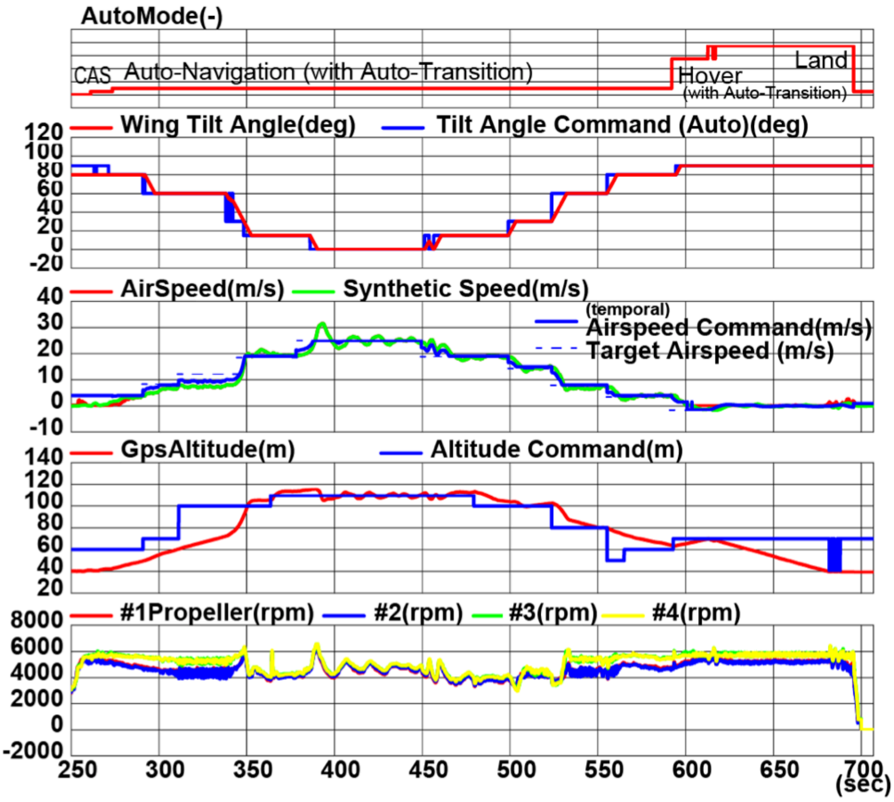
4.3.1 Transition Flight

Flight test results suggest that stable full transition flight from 90 (deg) wing tilt angle to 0 (deg) was accomplished using the proposed transition algorithm under moderate wind condition (wind speed on the ground was 2~3m/s). The algorithm properly generated temporally set appropriate airspeed commands, and also generated appropriate tilt angle commands well-suited for the target airspeed commands. No deviation from the safe flight envelope was observed when using the auto-transition algorithm.

4.3.2 Coordinating with the navigation and guidance loop

Flight along with the flight plan path, command speeds and altitude profile were maintained by the navigation and guidance control loop. During the transition, the control loop generated control commands by changing control strategies from "backside technique" to "front side technique" according to the tilt angles driven by the auto-transition algorithm.

(a) Snapshots



(b) Time History (Longitudinal)

Figure 6 – Auto Transition Flight Test Results

When the wing tilt angle changed from 15 (deg) to 0 (deg) completely, a certain amount of airspeed overshoot was observed. Although the airspeed did not deviate from the flight envelope, the algorithm should be revised to suppress the overshoot. This is one of our current research topics. Since the temporally set speed command was correctly generated, it seemed to be caused not by the auto-transition algorithm but by a degraded performance of the speed control loop which is coupled with the altitude loop at 15 (deg) through 0 (deg) wing tilt angle.

At around 450sec, right after 0 (deg) to15 (deg) wing tilt angle change was initiated, the tilt angle command immediately returned to 0 (deg) and then went to 15 (deg) again. This phenomenon can be explained as follows: When the aircraft started deceleration, there was certain amount of altitude deviation. The guidance controller adjusted it and the consequent maneuver to recover the altitude led to the speed increase. This speed increase exceeded the threshold of the tilt scheduler and the auto-transition algorithm subsequently gave the reverse the tilt angle command.

Although the algorithm worked correctly, it should be improved to provide more smooth transition. Revision of the speed and altitude guidance control performance to mitigate deviation, or modification of the tilt scheduler's threshold to allow larger overlap of the speed range between adjacent tilt angles would solve such problems and improves the practicality of the algorithm.

4.3.3 Coordinating with the navigation and guidance loop

During takeoff and landing hover phases, the QTW needs to fly at extremely low or negative (i.e. backward) airspeed. In general, accuracy of an airspeed sensor degrades severely in extremely low speed region and it cannot be used for the auto-flight controllers. Therefore, a synthetic speed is calculated in the on-board system to provide continuous speed status to the auto-flight controllers [6]. The synthetic speed adopts ADS (Air Data Sensor) airspeed when its output is high enough and otherwise adopts GPS ground speed. Sensor sources are exchanged when the airspeed output exceeds or goes back within a threshold (in the test flight it was 1.0 (m/s)). To switch the sensor sources moderately, both sensor data are mixed and the exchange is performed over 10 seconds. Time history showed synthetic speed ranging from negative (i.e. backward) extremely low negative speed to high speed was generated. Smooth transition to hover and vertical landing at 90 (deg) wing tilt angle was accomplished by the auto-transition algorithm and guidance controller using the synthetic speed.

5. Concluding Remarks

The automatic transition algorithm for the Quad Tilt Wing VTOL UAV was constructed and it was evaluated through the full transition flight.

Features of the algorithm are summarized as:

(1) To perform accelerated or decelerated transition, the algorithm automatically changes vehicle configuration by controlling wing tilt angles.

(2) Target wing tilt angle is determined by a target airspeed command input which is provided either by auto-navigation loop or by a GCS operator's intervention. The algorithm creates the airspeed command for gradual acceleration or deceleration and drive wing tilt angle to achieve the target airspeed.

(3) Coordinating with the navigation and guidance control loop, the algorithm enables automatic transition along with programmed flight path while maintaining its transition corridor (flight envelope).

Proposed algorithm was confirmed to provide sufficiently practical automatic transition capability to the QTW. Using the algorithm, the QTW can perform transition both within and beyond operator's visual line of sight. For more safe and precise mission capabilities, we will continue flight evaluation in various environmental condition and conduct detailed improvements on the algorithm as well as control loops.

6. Contact Author Email Address

mailto: muraoka.koji@jaxa.jp

7. Copyright Statement

References

[1] Bellamy, W eVTOL Investments Will Continue Billion Dollar Trend in 2021. Avionics International, Feburary/March 2021, 2021

[2] Hassanalian et.al. Classifications, applications, and design challenges of drones: A review. Progress in Aerospace Sciences, 91, pp.91-131, Elsevier, 2017.

[3] Muraoka, K, Kohno, T, Hozumi, K and Sato, M. Research on small UAS automation technologies for Mission Capabilities and Operator Independence Enhancement, Proc 58th JSASS Aircraft Symposium, JSASS-2020-5173-3D01, 2020 (in Japanese).

[4] Hartmann P, Meyer, C and Moormann, D. Unified Velocity Control and Flight State Transition of Unmanned Tilt-Wing Aircraft, AIAA Journal of Guidance, Navigation and Dynamics, Volume 40, Number 6, June 2017, https://doi.org/10.2514/1.G002168, 2017.

[5] Muraoka, K, Sato, M, Mochizuki, Y, Ito, Y, Sugimoto, M and Uchiyama. K. Automatic Guidance for a Quad Tilt Wing Small VTOL UAV. Proc 56th JSASS Aircraft Symposium, JSASS-2018-5064, 2018 (in Japanese).

[6] Muraoka, K, Sato, M, Mochizuki, Y, Ito, Y, Sugimoto, M and Uchiyama. K. Development of a Quad Tilt Wing Small VTOL UAV. Proc 57th JSASS Aircraft Symposium, JSASS-2019-5171, 2019 (in Japanese).

[7] Muraoka, K, Okada, N Kubo, D and Sato, M Transition Flight of Quad Tilt Wing VTOL UAV. Proceedings of the 28th International Congress of the Aeronautical Sciences, 2012.