JOURNAL OF AIRCRAFT
Vol. 47, No. 2, March–April 2010

Engineering Notes

Development and Conversion Flight Test of a Small Tiltrotor Unmanned Aerial Vehicle

Seongwook Choi,* Youngshin Kang,† Sungho Chang,†
Samok Koo,‡ and Jai Moo Kim§
Korea Aerospace Research Institute,
Daejeon 305-333, Republic of Korea

DOI: 10.2514/1.46180

I. Introduction

THE tiltrotor configuration was selected as the unmanned aerial vehicle (UAV) platform for the Smart UAV (SUAV) development program, which is one of the 21st Frontier research and development programs supported by the Korean government [1]. Some of the subsystems of the SUAV, such as the rotor system, drive system, and flight control system, were especially challenging for the Korea Aerospace Research Institute to develop, due to lack of previous development experience. To reduce the risk of failure during the development, the ironbird test of the rotor and drive system and flight simulation was conducted. Although the flight simulation mitigated the risk in the flight control system development, a downscaled model was constructed in an effort to ensure the safety in the flight test of the full-scale vehicle. The small-scale platform is shown in Fig. 1. It is expected from the flight test of the small scale model to enhance the understanding of the features of the actual tiltrotor vehicle.

The size of the downscaled model was determined to be $1/2.5$ (2 m overall length) of the full-scale SUAV (5 m overall length) so as to have large enough space for the simple flight control computer, the navigation system, and the other components such as the engine and actuators. The aerodynamic performance of the $1/2.5$-scale tiltrotor was analyzed using the in-house performance code. The calculated performance data were used for scheduling the control devices, such as the collective pitch of the rotors and the flaperon deflection, in the flight control logic.

In this Note, sizing and performance analysis of the downscaled tiltrotor are presented in which simple codes based on blade element and momentum theory were used. The conversion corridor of the tiltrotor was predicted and the nacelle tilt angle and air speed were compared with flight-test results. After a series of progressive flight tests, conversion flight from helicopter to fixed-wing mode was accomplished. This verified that the stability and control augmentation algorithm work properly in the flight control software. This small tiltrotor flight test is expected to reduce risks in flight test of the 5-m-span full-scale tiltrotor UAV called Smart UAV.

Received 6 July 2009; revision received 8 July 2009; accepted for publication 26 December 2009. Copyright © 2010 by the American Institute of Aeronautics and Astronautics, Inc. All rights reserved. Copies of this paper may be made for personal or internal use, on condition that the copier pay the $10.00 per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923; include the code 0021-8669/10 and $10.00 in correspondence with the CCC.

*Head, Air Vehicle Systems, Smart UAV Development Center. Member AIAA.

†Senior Researcher, Unmanned Systems, Smart UAV Development Center.

‡Head, Unmanned Systems, Smart UAV Development Center.

§Director, Smart UAV Development Center.

II. Sizing of the Tiltrotor

The small tiltrotor was geometrically scaled by $1/2.5$ of the SUAV, as shown in Table 1. The rotor system was not dynamically scaled, but the rotor control and hub components were designed to bear a similarity to those of the SUAV using the gimbaled hub and hub spring [2]. The major differences between the downscaled vehicle and the full-scale vehicle are engine and rotor speed controls. In contrast to the 550 hp turboshaft engine of the full-scale vehicle, a 15 hp two-cycle reciprocating engine was installed on the downscaled vehicle. The rotor speed also has a difference. The full-scale rotor operates in two speeds: 1604 rpm for the helicopter mode and 1284 rpm for the airplane mode. However, the downscaled model is set to be a single speed of 2000 rpm for the simplicity of the control system. If the Mach number was scaled, the $1/2.5$ rotor needs to have the rotor speed over 4000 rpm, which exceeds the mechanical limits of the off-the-shelf components. Instead, a lower rotor speed was selected for both the helicopter and airplane modes. The performance calculation indicated that 60 kg of gross weight is available from the 15 hp engine, and the mission gross weight was determined to be 38 kg for the typical flight.

III. Performance Analysis

The performance analysis code named SPAC (Smart UAV Performance Code) was developed and used for the performance estimation. The code has a capability to calculate the three modes of tiltrotor flight: hover, transition, and cruise. SPAC consists of several modules. The generalized input module enables the code to calculate various types of mission profiles. The aerodynamic performance module for the rotor is based on a blade element and momentum theory. The rotor flapping equations and vehicle trim equations are combined to calculate the attitudes of the rotor and airframe. SPAC was used for the design of both the full-scale and small-scale vehicles.

The hovering performance of the $1/2.5$-scale proprotor was calculated as shown in Fig. 2. The result was used for investigation of the hovering capability as well as for the initial sizing of the rotor. Figure 2 shows the thrust generated from the hovering rotor for the collective pitch measured at the 75% span of the rotor blade. The two points marked on the plot indicate the measured data from the frame vehicle, which consist of the rotor-drive system and engine [3]. Test points 1 and 2 are hover data with a rotor speed of 2000 rpm for the gross weight of 40 and 50 kg, respectively. The two test points show good agreement with the estimation at the corresponding rotor speed. Considering the 12% download ratio (which is the weight increment due to the rotor downwash on the wing and body) and 5% lift-up margin allocated for the 50 kg vehicle, the required thrust was estimated to be around 60 kg.

The performance at the conversion flight was estimated for the nacelle tilt angle from 80 to 0 deg to determine the proper vehicle attitude during the conversion flight. Figure 3 shows nacelle tilt angle versus vehicle speed at various vehicle angles of attack. As the angle of attack increases, the conversion path moves from the right to the left approaching the vehicle stall boundary. On the other hand, for the low angle of attack, the conversion path approaches the engine power limit. Considering the two boundaries, a conversion corridor was recommended to be a 4 deg of angle of attack.

IV. Flight Control

The ground and flight tests were conducted using rate stability augmentation system and attitude stability and control augmentation system feedback [4,5]. One of the main purposes for the scale-model flight test was the evaluation of the control law.

Fig. 1 A 2-m-span tiltrotor UAV in hover.

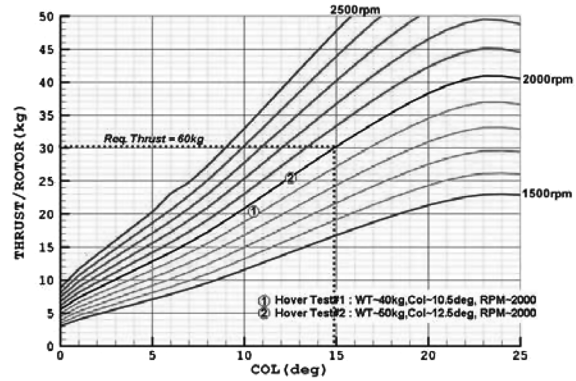


Fig. 2 Collective pitch—thrust curve for hover.

The tiltrotor requires multiple control structures corresponding to different flight modes, because the flight characteristics significantly vary during the transition from the helicopter mode to the airplane mode [6]. In this Note, a common structure of the control law was used for all the configurations, as shown in Fig. 4. For the control law design, a nonlinear simulation model was developed based on the mathematical dynamics model of a manned tiltrotor [7]. The attitude SCAS control law covering from the helicopter mode to the airplane mode was evaluated through the scale-model flight test.

The rotor governor was used to keep the rotor speed steady during all the flight phases. The governing system regulates the blade pitch to maintain the constant rotor speed, while the pilot still has the control over the engine through the throttle command. For the tiltrotor configuration, the rotor governor is known to be more effective than the engine governor, because the flight speed is excessively sensitive to the rotor blade pitch angle in the airplane mode [6].

At the beginning of the flight test, the rate feedback SCAS control law was used in order to evaluate flight characteristics of the tiltrotor. For the later flight tests, attitude SCAS was added in order to ensure that the external pilot's (EP's) workload during the pitch and roll attitude is automatically maintained, while the nacelle tilt angle was still controlled by the EP. At the same time, in order for the vehicle to stay in the conversion corridor, the airspeed also had to be controlled by the EP, increasing its workload. After the successful flight

Table 1 Scaling of the design parameters

Specification	Full scale	1/2.5 scale
Weight		
GW, kg	995	38
Payload, kg	40	N/A
Fuel, kg	280	3.2
Engine		
Type	Turboshaft	Reciprocating
Max power, hp	550	15
Rotor		
Hub type	Gimbal	Gimbal
Radius, m	1.433	0.573
Disk loading, kg/m^2	77.1	18.4
RPM_HC	1604	2000
RPM_AP	1284	2000
Tip speed_HC, m/s	241	120
Tip speed_AP, m/s	193	120
Gimbal spring, Nm/rad	359.0	11.1
Flapping inertia, kg m^2	1.636	0.017
Lock number	3.140	3.140
DEL3 angle, m^2	−15.0	−15.0
Wing		
Chord, m	0.80	0.32
Span, m	4.00	1.60
Wing loading, kg/m^2	310.9	74.2
Fuselage		
Length, m	4.96	1.98

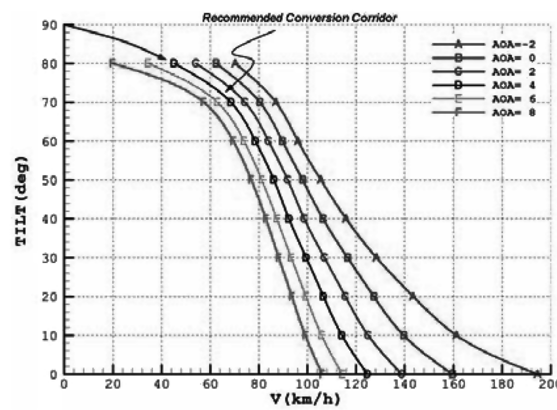


Fig. 3 Speed—tilt angle curve for the conversion flight.

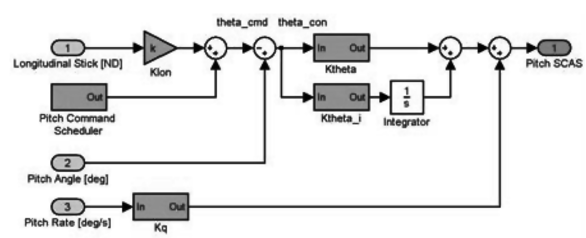


Fig. 4 Block diagram of the pitch-attitude SCAS.

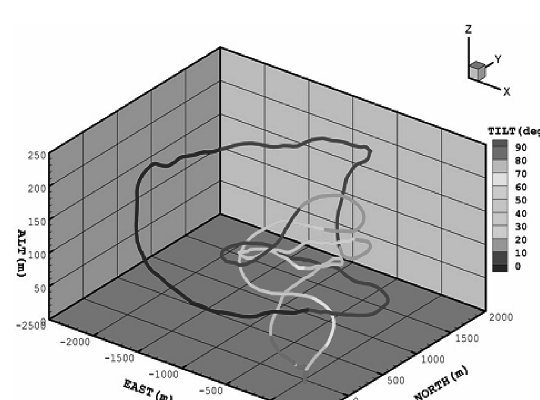
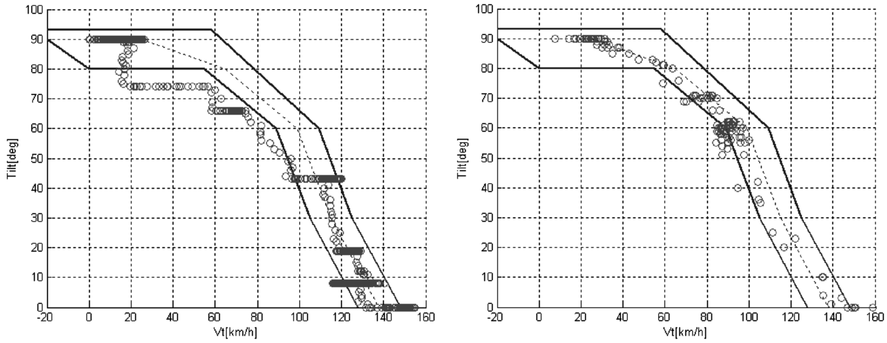


Fig. 5 Nacelle tilt angle and flight trajectory acquired from manual-tilt flight test.



a) Manual tilt flight **b) Automatic tilt flight**

Fig. 6 Conversion corridor plot from tilt flight test.

reaching the nacelle tilt angle down to 0 deg by the EP's manual-tilt command, the automatic nacelle control logic prevented deviation from the conversion corridor.

The structure of the attitude SCAS in pitch axis is shown in Fig. 4. The pilot input and the pitch-attitude feedback generate the attitude error command and it is augmented by the proportional and integral gains. Because of the unusual tendency of pitching up in transition at the high tilt angle and pitching down at the low tilt angle, the integrator gain was determined to handle the situation efficiently. The integrator gains in the pitch and roll axes were designed to remove the steady-state errors as well as to give more controllability to the pilot. The pitch-rate feedback was also included in the inner loop of the pitch-attitude SCAS to increase the damping in the pitch motion.

V. Flight Test

In the early flight-test phases, the EP had to manually control the nacelle tilt angle in order to stay in the conversion corridor. Figure 5 shows a flight trajectory while varying the nacelle angle.

The trajectories, in terms of the corridor parameters, of the conversion flight with the manual and automatic tilt controls are compared in Fig. 6. During the flight with the manual-tilt control, despite the pilot's effort, the trajectory reveals that the vehicle was not successfully maintained in the allowable corridor. For the flight with automatic nacelle tilt, the tilt angle was automatically determined based on the airspeed, and it can be noted from the figure that the speed deviation at the given nacelle tilt angle is much smaller than that of the manual-tilt flight. The trajectory remains in the allowable corridor, except for some scattered data in the left side of the corridor boundary that was caused by the abrupt deceleration in the airplane mode flight. The limited pitch-attitude authority in the conversion mode could not maintain the vehicle within the conversion corridor. The limiter in the conversion control loop reduced the nacelle tilt slightly less than required.

VI. Conclusions

A 2-m-span small tiltrotor UAV was developed, making full use of the available parts from the radio-controlled helicopter community. The vehicle was equipped with the flight control computer and was successfully controlled by the EP. The control logics eventually implemented on the flight control computer enabled the vehicle to perform successful conversion flights. The flight test verified that the stability and control augmentation algorithm worked well in the flight control software. The simple aerodynamic performance estimation and vehicle sizing based on the first principles contributed to reduction of the design period. The experience of the flight test on the downscaled model became a valuable asset to the designers and flight-test staffs for the full-scale vehicle development. This experience is now being reflected in a full-scale flight-test program.

Acknowledgements

This research was performed for the Smart UAV Development Program which is one of the 21st Century Frontier R&D Programs funded by the Ministry of Knowledge Economy in Korea.

References

[1] Oho, S. H., Kim, S. J., and Lim, C. H., "Overview of Smart UAV Development Program," *Journal of the Korean Society of Mechanical Engineers*, Vol. 46, No. 2, 2006, pp. 34–80.

[2] Bailey, B., Snowden, M., Bartley, M., Phelps, A., Lee, M. K., and Kim, J. M., "Design of an Advanced Composite Proprotor Blade for the Tilt-Rotor Smart UAV," *AHS 62nd Annual Forum* [CD-ROM], AHS International, Alexandria, VA, May 2006.

[3] Chang, S. H., Choi, S. W., Kim, J. M., and Koo, S. O., "Development of the Scaled Vehicle of Smart UAV," *Proceeding of KSAS Spring Conference*, Korean Society for Aeronautical and Space Sciences, Yongpyong, Korea, 2007, pp. 389–392.

[4] Kang, Y.-S., Park, B.-J., Yoo, C.-S., Chang, S.-H., Choi, S.-W., and Koo, S.-O., "Comparison of Tethered Hover Test and Ground Test Results for Small Scaled Tilt Rotor Aircraft," *Rotor Korea 2007* [CD-ROM], AHS International, Alexandria, VA, Oct. 2007.

[5] Kang, Y.-S., Park, B.-J., and Yoo, C.-S., "Control Law Modification According to Flight Test of Small Scaled Tilt Rotor UAV," AIAA Guidance, Navigation and Control Conference and Exhibit, AIAA, Paper 2008-6334, Aug. 2008.

[6] Fortenbaugh, R. L., Builta, K. E., and Schulte, K. J., "Development and Testing of Flying Qualities for Manual Operation of a Tiltotor UAV.," AHS International, Alexandria, VA, May 1995, pp. 299–320.

[7] Harendra, P. B., Joglkar, M. J., Gafey, T. M., and Marr, R. L., "A Mathematical Model for Real Time Flight Simulation of The Bell 301 Tilt Rotor Research Aircraft," NASA CR-114614, 1973.