KARI TILTROTOR UAV FLIGHT TEST
AND
PERFORMANCE ENHANCEMENT STUDY

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Abstract

KARI tiltrotor UAV, called Smart UAV (SUAV), performed flight tests in different modes of flight including helicopter, conversion and aircraft modes. The flight test was successfully performed after extensive risk control efforts. Extensive ground tests with an ironbird and 4-degree-of freedom test rigs enabled to correct the faults both in software and hardware in the SUAV system. Flight tests started with the vehicle tethered from top until clear the unexpected defects in the flight control system. It took time to begin the untethered flight test but the conversion flight from helicopter to aircraft mode could be achieved in a short period due to previous risk mitigation efforts. The flight tests have been performed in a progressive way. It started firstly with external pilot's manual control but the control was handed over to internal pilot later. After various flights for performance check and handling quality, fully autonomous flight was demonstrated flying programmed navigation points.

Performance enhancement study was performed since potential customers asked longer endurance with the tiltrotor UAV. One approach was to attach an auxiliary wing to the nacelle. This approach was chosen since it can be implemented through minimum modification from the basic platform. Preliminary prediction indicates that 26% increase of the endurance can be achieved through the auxiliary wing extension. The other approach was to find a long endurance flight condition in the all flight modes. The performance prediction with a 60%-scale tiltrotor UAV indicates that the endurance can be extended up to more than 8 hours when the rotor tilts forward 30 degrees and the flap deflects 21 degrees. The longest endurance in the fixed-wing mode was 5.5 hours in the 60%-scale tiltrotor UAV.

Introduction

Tiltrotor development in Korea started in 2002, when the tiltrotor development was still in big controversy in US due to continual accidents with V-22 flight tests. Ambitious engineers at KARI entered a competition to win the big research fund called '21st Century Frontier R&D Program' and won the fund promising to develop a UAV system which has VTOL and high speed capability. Feasibility study led to select a tiltrotor configuration as a platform. A 5m-span tiltrotor with 1-ton weight was designed. Extensive analyses and wind tunnel tests were performed for performance prediction and flight control design. Key technologies were explored and validated with ground tests (Ref. 1 & 2)

The tiltrotor was an unusual and unfamiliar vehicle to KARI engineers that it was decided to develop small-scale vehicles to understand the unknown characteristics of the tiltrotor. Different sizes and types of the small scale model was developed and tested. A 30%-scale model was first developed from the RC(Radio Control) model with electric motor engine. Later 40%-scale model was developed to mount flight control computer and other navigation devices. The small scale vehicle test contributed not only to understand the special characteristics of the tiltrotor but to mitigate the risks in the tiltrotor UAV system. Ironbird test rig for the rotor and drive system was adopted in the small scale vehicle development. The 4-degree-freedom test rig and tethered flight settings were also adopted here. Many faults were found and corrected through the ground tests and tethered flight tests but accidents and incidents were inevitable in the small scale test

The test method developed during the small-scale test was applied to the full-scale SUAV, which contributed to reduce risks in the following flight tests.

Tethered Flight Test

Tethered test was designed to reduce risks before starting the maiden flight but it was frequently used to check the flight readiness. The vehicle was hung from the tower crane using a harness (Fig. 1). The harness was designed to hold the vehicle with solid parts so that the tethering cable cannot hit the rotor blades. The EP(External Pilot) could control the vehicle in hovering motion within limited boundary. The rotor speed control was verified by keeping the required RPM within the design limit. The rate SAS(Stability Augmentation System) feedback, longitudinal and lateral cyclic gains in the control surface mixer were tuned at hover mode. Several errors and deficiencies were found during the tethered test and were fixed properly before the flight test.

With repeated tethered flight tests and flight control software correction, SCAS(Stability and Control Augmentation System) mode flight control was improved so that the EP can control the vehicle in a very stable condition. Fig. 2 shows pitch attitude oscillation at early stage. An improved pitch attitude oscillation level is shown in Fig. 3.

Fig. 1 Tethered flight of the full-scale Smart UAV

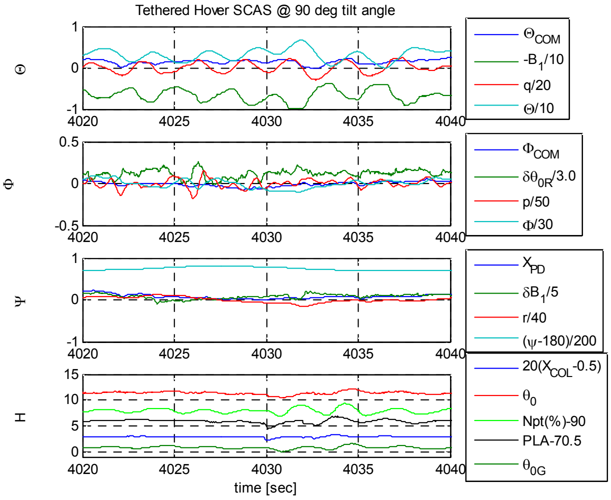


Fig. 2 Test results of the first tethered hover flight

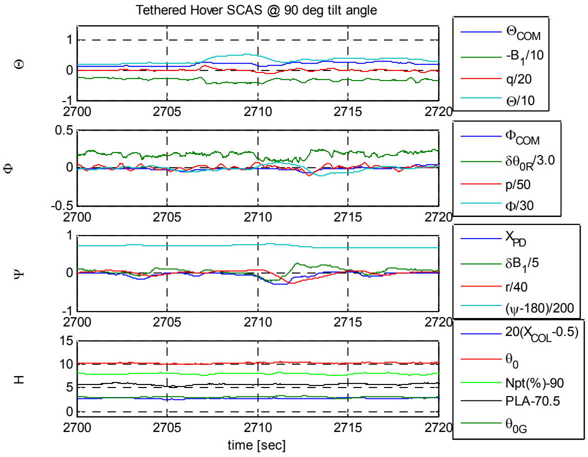


Fig. 3 Test results of the improved handling qualities in tethered hover flight

Helicopter Mode Flight Test

The flight test was progressively performed from helicopter mode to conversion and airplane mode. Helicopter mode flight test included manual and automatic take-off and landing. The forward flight speed was increased up to 100km/h where the nacelle tilt angle was 80 deg. The vehicle was manually controlled by EP at first. Automatic flight control was employed soon after the automatic takeoff and landing mode flight was verified. The helicopter mode test was very important since it is the starting point of the control gain schedule in the flight control design. The control system was extensively verified first in the helicopter mode test. The gain schedule data was reflected progressively to the following conversion and aircraft mode tests. Fig. 5 shows test result from the SUAV in pre-programmed mode and automatic recovery mode test. The IP(Internal Pilot) gave return home command during pre-programmed mode flight and the vehicle demonstrated returning to the designated point. The return home command is automatically given in case there is communication failure between the ground control system and the vehicle.

Fig. 4 Full- scale SUAV in hover mode flight

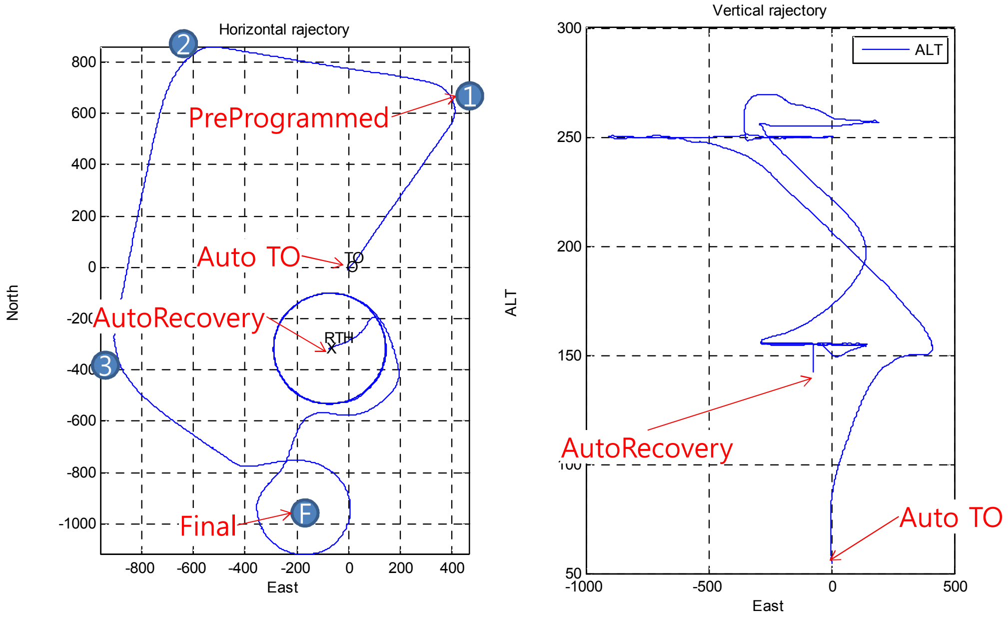


Fig. 5 Flight trajectory from SUAV hover flight with pre-programmed mode

Conversion Flight Test

The nacelle tilted further in the conversion mode from 80 deg to 0 deg(Fig.6). The forward flight speed was increased so that the nacelle tilt angle was incrementally increased by 10 deg. At each tilt angle flight characteristic was monitored while the vehicle was controlled to make ascending and descending flight with 8-patterned flight. The SUAV flight control design specification was adopted from existing helicopter and fixed-wing design specification since tiltrotor handling quality specification was not available at that time. Fig. 7 shows trajectories resulted from climbing and descending flight while the nacelle tilt angle incrementally varied by 10 degrees.

Fig. 6 Full- scale SUAV in conversion mode flight

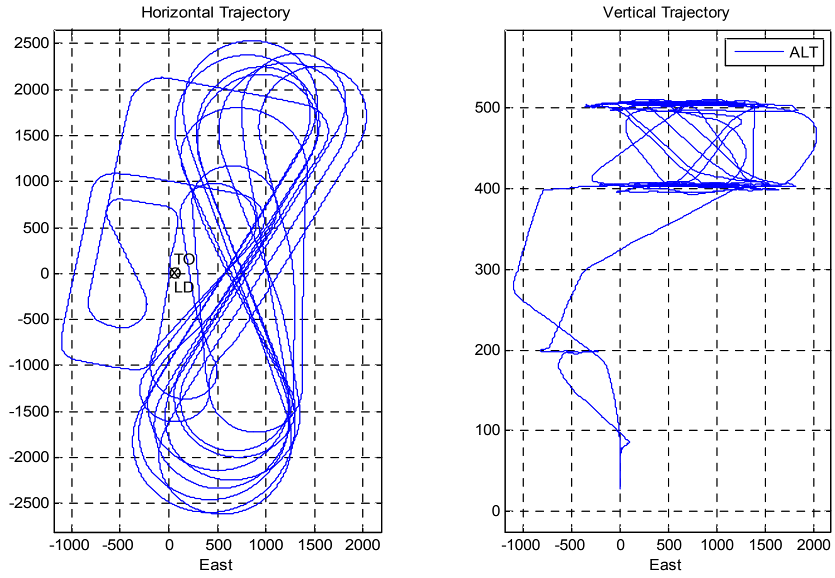


Fig. 7 Flight trajectory from SUAV conversion flight test at various tilt angles and altitudes

After all of the control performance criteria were satisfied at all tilt angles, continuous conversion flight was made as shown in Fig. 8. The forward flight speed and nacelle tilt angle were within the designed conversion corridor. After the vehicle reached a fixed-wing mode speed, the rotor rpm was reduced from 98% to 82% level. This rpm reduction was designed to increase fixed wing mode performance. Drastic noise reduction was recognized on the ground.

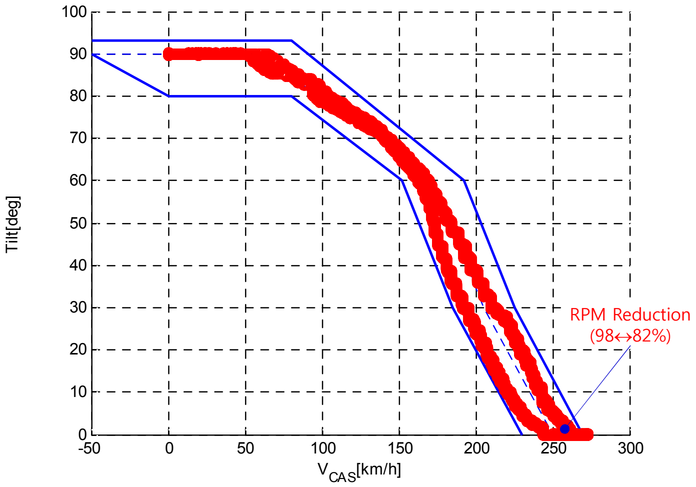


Fig. 8 Speed and tilt angle result from continuous conversion flight of SUAV

Airplane Mode Flight Test

After achieving successful helicopter and conversion mode flight, fixed-wing mode flight test was performed (Fig. 9). High speed and high altitude flight performances were to be demonstrated here. Flight range for the high speed test had to be expanded up to 8km-diameter circle exceeding the KARI flight test site. The vehicle was guided over the sea area as shown in Fig. 10. Flight performance test was made following the circle with point navigation control. After the vehicle reached airplane mode speed, 250km/h, the rotor rpm reduced to 82% level. Then the vehicle raised the altitude up to 3 km. With each 1 km incremented altitude, the vehicle made 4km-radius circular flight with 25-deg bank angle. At 3km altitude, the vehicle reached true air speed of 440 km/hr (Fig. 11).

Fig. 9 Full- scale Smart UAV in airplane mode flight

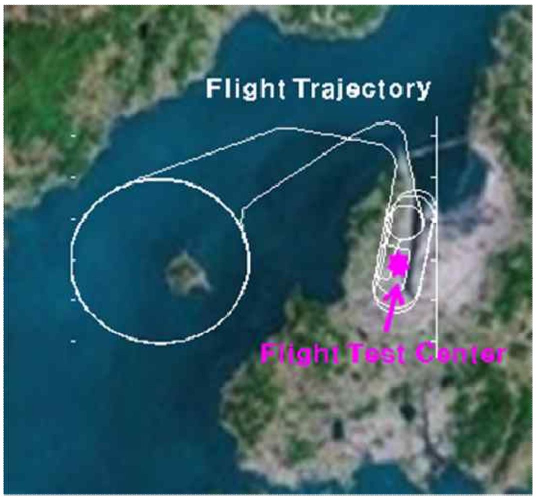


Fig. 10 Flight trajectory over KARI test site obtained from SUAV airplane mode flight

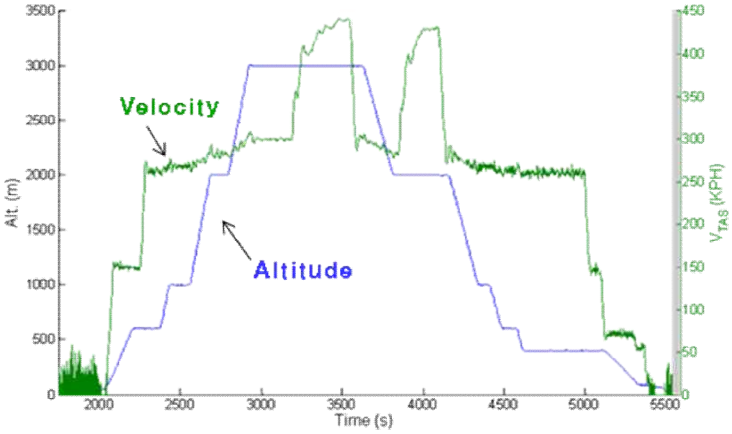


Fig. 11 SUAV Flight test result from SUAV airplane mode test showing time history of speed and altitude

Performance Enhancement Study

Performance enhancement study was performed since potential customers asked longer endurance with the tiltrotor UAV. One approach was to attach an auxiliary wing to the nacelle (Fig. 12). This approach was chosen since it can be implemented through minimum modification from the basic platform. The nacelle-attached wing concept is expected not to increase wing download by rotor wake in hover since the extended wing rotates with nacelle (Fig. 13). However it increases the wing aspect ratio and contributes to increase the endurance.

Performance enhancement was predicted analytically by comparing performances between a baseline and an extended-wing configuration. The aerodynamic database of extended-wing configuration was calculated through CFD analysis. Full aircraft trim analysis was performed to predict the required power and performance parameters. Endurance and range factors of the two configurations were compared to check the potential performance improvement in the airplane-mode.

Prediction results show that endurance parameter with extended wing increases 26% compared with baseline (Fig. 14). The range parameter is predicted to increase by 16% at 3 km altitude (Fig. 15)(Ref. 3). The speeds for the maximum endurance and range are shown to decrease to some extent.

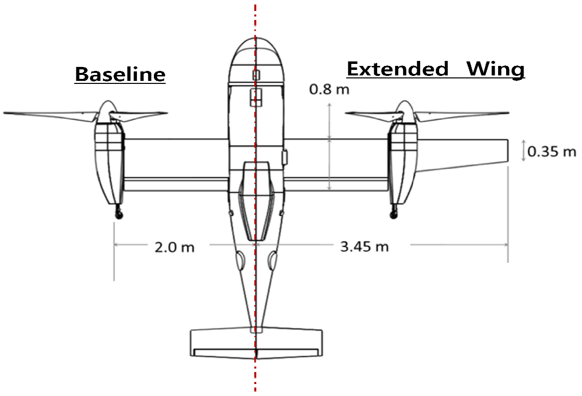


Fig. 12 Baseline and extended-wing configuration of the tiltrotor UAV

Fig. 13 Tilting concept of the extended-wing tiltrotor UAV

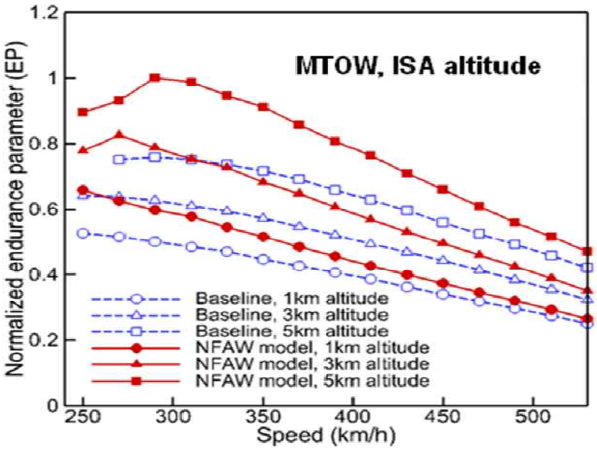


Fig 14 Endurance parameter increase due to extended wing in tiltrotor UAV (Ref. 3)

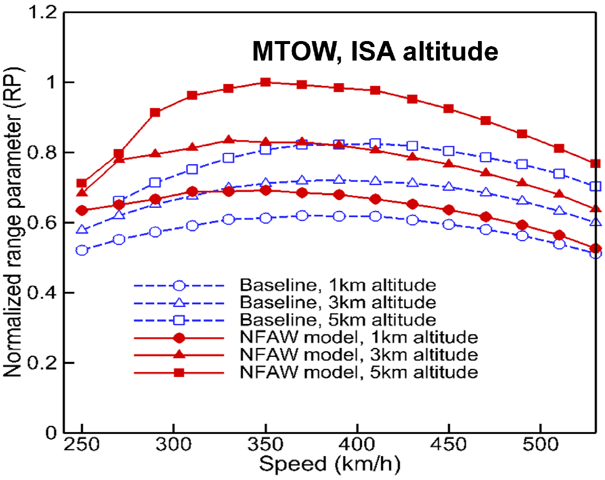
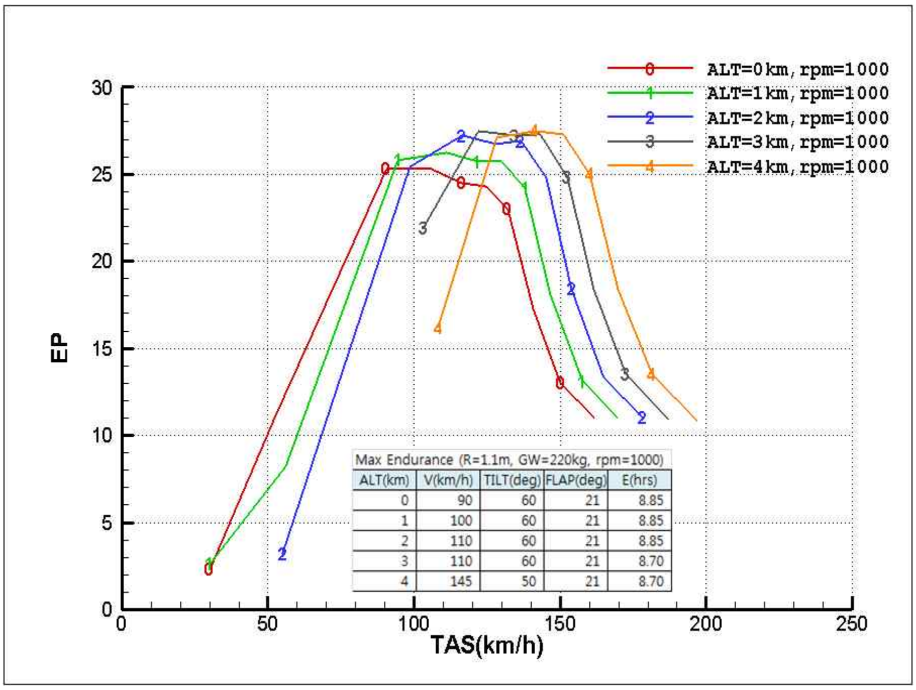


Fig 15 Range parameter increase due to extended wing in tiltrotor UAV (Ref. 3)

The other approach was made by finding long endurance flight condition in the three flight modes. The performance analysis used in-house code, where the aerodynamic performance module for the rotor is based on a blade element and momentum theory. Rotor flapping equations and aircraft trim equations are combined to calculate attitude of the rotor and airframe (Ref. 1). The performance prediction with the 60%-scale tiltrotor UAV indicates that the endurance can be extended up to more than 8 hours when the nacelle tilts forward 30 degrees, the flap deflects 21 degrees and the rotor rpm reduces by 20% (Fig. 16). The longest endurance in the fixed-wing mode was predicted by 5.5 hours in the 60%-scale SUAV



Max Endurance (R=1.1m, GW=220kg, rpm=1000)

ALT(km)	V(km/h)	TILT(deg)	FLAP(deg)	E(hrs)
0	90	60	21	8.85
1	100	60	21	8.85
2	110	60	21	8.85
3	110	60	21	8.70
4	145	50	21	8.70

Fig. 16 Maximum endurance predicted at conversion flight mode

Conclusions

KARI tiltrotor UAV has been developed since 2002 and demonstrated all modes of flight in 2011. There were many challenges in developing the unusual and unconventional tiltrotor aircraft.

Extensive risk mitigation activities were performed using both small- and full-scale vehicles. Extensive ground tests and tethered flight tests contributed to safe flight test and fast progress from maiden flight to full conversion flight.

Performance enhancement was requested from potential customers. Extended-wing approach indicates that 26% increase of endurance is expected in airplane fight mode. The other approach indicates that the endurance can be increased up to 8 hours when the rotor tilts forward 30 deg, the flap deflects 21 degrees and rotor rpm reduces 20%. The Baseline tiltrotor UAV has 5.5-hour endurance.

References

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