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DEVELOPMENT OF SMART TILT-ROTOR UAS AND THE BEGINNINGS OF KOREAN CIVILIAN DRONES

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Abstract

Past and current situation of Unmanned Aerial Vehicle (UAV) development and civilian application in Korea is presented with description of the various UAV related terminologies. Smart UAV (SUAV) development and test is presented in detail, where the SUAV was developed by Korea Aerospace Research Institute (KARI) and Korean industries. Major features of SUAV are also presented including the developmental procedure. This paper also includes activities regarding development of small UASs in Korea, where targeting operation area of the small UASs in Korea and core technology development plan is also included in this paper.

1. General Introduction

1.1 Terminology Definition

Unmanned aerial vehicle (UAV), generally known as a drone, is an aircraft without human pilot aboard. Its flight is controlled either autonomously by onboard computers or by remote control of a pilot on the ground or on another vehicle. UAS (Unmanned Aircraft System) consists of the UAV airframe with propulsion, avionic and telemetry systems, and payloads configured of electro-optic/infrared (EO/IR) camera, radar, etc. Data link system, ground control system and ground support systems are also included.

The terms of UAV (Unmanned or Unpiloted Aerial Vehicle), UAS, and that of RPV (Remotely Piloted Vehicle), RPA[S] (Remotely Piloted Aircraft [System]) are differently used depending on whether it is autonomously controlled or not. In this paper the multi-rotor

type small UAVs are called Drones and in other cases the UAS will be used.

1.2 Worldwide History of UAS and Drones

United States, former Soviet Union, Israel started to develop the military UAS in the early stages, but their full-fledged development of UAVs began from the 1960s. They were used for monitoring the theater of war in order to reduce casualty loss during the war. For example Israel used decoy UAVs during the 4th Arab-Israeli war in 1973. Other examples are Kosovo war in 1999, Afghanistan war in 2001 and Iraq war in 2004. Global Hawk and Predator of the United States and Heron of Israel were well developed that their UAS operation even incurred remarkable damage to the enemy.

In 2010s, many companies have prepared for the growing demand for civilian application of the UAVs. Amazon in the USA, DHL in Germany and Alibaba in China are developing drones for delivery to customers. Facebook and Google in USA want to develop the high-altitude and long-endurance UAS for the purpose of enabling the internet communication all over the worlds. The international UAV flight rules have been prepared by International Committee of Aviation Organization (ICAO) along with international aviation authorities. Nevertheless broad use of civilian UAS seems to take a long time due to unresolved safety issues.

1.3 Korean History of UAS and Drones

Since 1980s, military UAS was developed by Agency of Defense & Development (ADD) which is a defense research & development institute funded by Korean Government. Various military UAS programs were initiated by the ADD until recently along with industries such as by Korea Aerospace Industries (KAI) and Korean Air (KA). There are also various UAV subsystem suppliers such as LIG Nex1, Hanwha and STX Engines. Smaller UAS were developed by several domestic companies.

In the civilian sector, in 2002, the smart tilt-rotor UAS development program was launched by KARI, the aerospace R&D institute funded by the Government, together with several Korean industries such as KAI, LIGNex1, UCON systems. Small-scaled flight demonstrator of the tiltrotor UAV successfully achieved the mission of fully autonomous tilt rotor flight in 2008. Full scale flight demonstrator successfully demonstrated the transition and high-speed flight at the Goheung KARI Flight Test Center by December of 2011(Fig. 1). Research and development of the various smart technologies such as autonomous flight including take-off and landing, real time health monitoring, sense and avoid of collision, automatic mission reconfiguration were also included in the smart UAV Development Program.

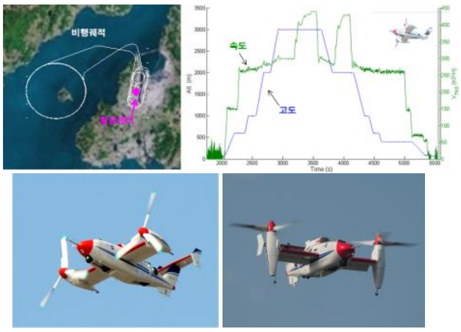

Fig.1. Flight Trajectory and Speed & Altitude of Smart UAS Flight Test (One hour Flight with Max. Speed of 440km/h at 3km Alt.)

Since 2010, UCON systems and Sungwoo have developed a small helicopter-type UAV for spraying pesticides. Recently multi-rotor industrial drones are rapidly expanding market in Korea. The small companies such as NES & TEC, Gryphon Dynamics, KASCOM and TOPUAV are developing the multi-copter industrial drones attempting to commercialize them. Multi-rotor drones are mainly used by the aerial photographer, broadcasters, movie studios, and many farmers for different purposes. The communication services company LG U + has demonstrated the real-time control and image transmission and reception in March 2014 using small quad-copter drones. (Fig. 2)

Fig.2. Small and Medium-sized Multi-copter systems are under developing

It can be summarized that the military UAS development started in 1980s and civilian UAS in 2000s in Korea. The civilian drone development in Korea started in early 2010s are in progress expanding their applications. This paper is describes detailed procedure of the SUAV development since it is the first civilian UAS and Drones in Korea.

2. SUAV Development and Operation

2.1 Tilt-rotor aircraft

The tilt rotor has recently been risen as a strong alternative to the future high speed vertical take-off and landing (VTOL) air vehicle concept both in civil and military applications. The most important advantage of the tiltrotor concept is known to have higher flight speed and endurance performance superior to conventional helicopters. In the early stage of the military tiltrotor aircraft development, V-22 Osprey of Bell-Boeing, several unexpected mishaps happened. However, in spite of many adversities, the tilt rotor concept has been actively researched and developed. Recently, the commercial tiltrotor aircraft, AW609 of Agusta-Westland has been on the certification process by European Aviation Safety Agency (EASA) and Federal Aviation Administration (FAA). (Fig.3)

Fig.3. Bell-Boeing V-22 Osprey and Agusta-Westland AW609

One of the most prominent trends in the recent aeronautical field is an emergence of UAS. Many people anticipate that in near future the UAS will replace many roles of the manned aircraft, especially in surveillance missions. These days, various configurations of unmanned aerial vehicle have been designed and utilized in many applications. Tilt rotor UAS is one of those noticeable applications. Tiltrotor UAS has both advantages of the fixed wing and rotary wing aircraft. It can take off and land vertically, and cruise with high speed and fuel efficiency close to the fixed wing aircraft. (Fig.4)

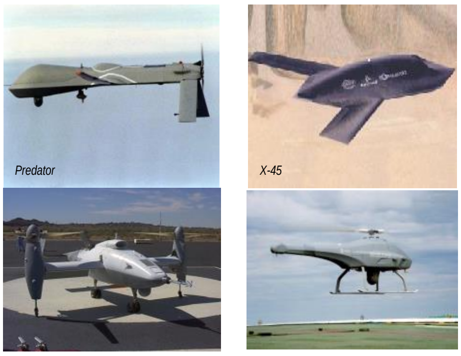

Fig.4. Various UAS Type: Fixed Wing, Tilt-rotor, and Helicopter

2.2 Specification and Configuration

The request for proposal (RFP) of the Smart UAV (SUAV) is shown in Fig. 5. The length is 5m, and the maximum takeoff weight is 1,000kg, and the maximum payload is 90kg. The maximum and maneuver speeds are 500 km/h and 400 km/h, respectively. The operation altitude and endurance time are 6 km and 5 hours. Highly reliable design and operating concepts were implemented in the critical subsystems such as power train, flight control and avionics systems. SUAV can fly in three flight modes; helicopter, conversion and airplane modes. After vertical takeoff in helicopter mode, the rotor is tilted following preprogrammed conversion flight envelope. Various smart technologies have been applied to SUAV, fully autonomous flight including take-off and landing, real time health monitoring, see-and-avoid collision avoidance and automatic mission reconfiguration.

Fig.5. RFP of SUAV

One SUAV set is composed of 5 aerial vehicles with a Ground Control System (GCS) and Ground Support Systems (GSS). (Fig.6) Smart technologies are mainly incorporated in the platform and payload systems. The SUAV applications could include surveillance, monitoring, exploration and telecommunication.

Fig.6. SUAV 1 Set Configuration

2.3 Design and Integration

In the initial stage of the SUAV development, tiltrotor was selected as one of baseline platform configurations through intensive trade study. From the study, tiltrotor showed more efficient performance for SUAV requirements over the other candidates of stopped rotor and compound gyrocopter. Especially tilt rotor showed much higher endurance in the mission of surveillance because it could be operated by airplane mode in the mission profile.

Various methodologies of design, analysis and evaluation methods were applied to SUAV design. Figure 7 shows one of CFD analysis results and wind tunnel test setting of the SUAV. Three configurations of isolated rotor, unpowered and powered configurations were analyzed by computational method with dynamic overlapping grid scheme. Wind tunnel tests were performed for evaluating the aerodynamic data of SUAV. Three types of unpowered static, powered static and dynamic wind tunnel test models were designed and fabricated. Most of wind tunnel tests, except forced vibration test, were performed in KARI 3x4m subsonic wind tunnel. From the extensive

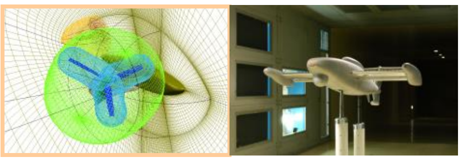

Fig. 7. CFD Analysis and WT test

test valuable data were extracted to be utilized in evaluation of prop-rotor efficiency, control surface effectiveness and dynamic stability.

Airframe structure of SUAV was designed to minimize weight and fabrication process under the given design requirements of vibration, dynamic stability, load, strength and operation environment. Composite materials were used in many portion of the structures to reduce weight, and two component parts were used to reduce e the cost. The first bending vibration mode from the finite element analysis was studied by FEM tool, and various static and dynamic structural tests were performed in the evaluation process.

The power plant system of SUAV can be divided by engine, drive line and nacelle conversion systems. A turbo shaft engine of P&W 206C was located at center fuselage and drives both rotors through center and pylon gearboxes. (Fig.8)

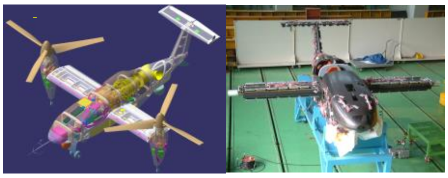

Fig.8. FEM Model and Static Structural Test

The drive line includes gear boxes, drive shafts, cooling and lubrication systems. The super-finished gears were developed and used in the gear boxes to enhance the performance and durability. A dry sump type of lubrication concept with oil jets was applied to all three gearboxes. Nacelle conversion actuators located at the wingtips drive the nacelles including rotor system between the tilt angles of helicopter and airplane modes. SUAV has three-bladed, gimbaled, stiff-in plane rotor system. The SUAV gimbaled hub was designed based on automotive style mechanical constant velocity joint that uses large ball bearings driving deeply grooved hub elements, and tension-torsion strap transferring CF force of blade to hub. All the actuators in rotor pitch control and nacelle conversion are electric motor driven with redundancy.(Fig.9)

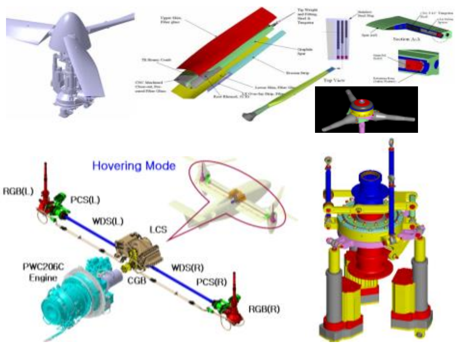

Fig.9. Prop-Rotor System Design

The flight control system (FCS) of SUAV was developed for fully autonomous flight with health monitoring and collision avoidance functions. Hardware of the FCS was composed of digital flight control computer, local precision position system, DGPS/INS, collision avoidance system, electric actuator system, air data system, and radio altimeter. The operational flight program (OFP) of SUAV was designed with fault detection and intelligent mission control algorithms. Both hardware and software of SUAV FCS has dual redundancy.(Fig.10)

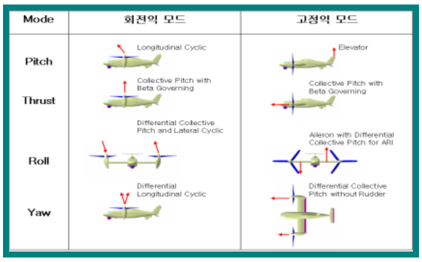

Fig.10. OFP Autonomous Flight Control Logic

The communication system of SUAV was designed to have the minimum 95% reliability in 200km distance with double channels on up and down links respectively. The ground control system (GCS) of SUAV are composed of pilot bay, navigation bay, external pilot box, ground control vehicle, shelter assembly system, observation bay and transmission bay. Major functions of the GCS are aircraft control, data link control, flight information display, management, mission planning and fault-detection. (Fig.11)

Fig.11. Ground Control System

2.4 Test and Evaluation

Function, performance and reliability of the SUAV have been validated by various tests such as component test, interface test, ground integration test, environment test, Iron-bird test, four degree of freedom (4-DOF) ground test, tethering test, small scaled flight demonstrator test and full scale flight test. The full scale SUAV flight test was totally completed in December 2011 followed by the previous small-scale flight tests.

An electro-magnetic interference (EMI) test of SUAV at KARI environmental test facility was performed.(Fig.12) Although all the subsystems constituting SUAV were provided after passing their separate EMI tests, the whole integrated configuration of SUAV had to be finally checked to confirm the interference effect among the subsystems. HILS test performed to simulate the flight behaviors of the SUAV before the real flight. The ground pilot could get training for SUAV operation through the HILS, reducing risk in the real flight operation. During the evaluation process of flight behaviors in HILS and real operations such as 4-DOF and tethering test by the pilot, all the gathered data were used as an input to compliment the flight control algorithm of digital flight control computer (DFCC). In real free flight, SUAV flies a fully autonomous mode with the preprogrammed command under monitoring by the pilot in the GCS.

Fig.12. EMI/EMC and HILS Test

One of the unique tests in the development process of SUAV was Iron-bird test. The power plant system of SUAV was verified by iron-bird ground test. Iron-bird was served as a test bed for developmental testing of the power plant system. The function and performance of engine, drive line, nacelle conversion and rotor systems were evaluated by a building block approach of the iron-bird test concept. It could save time and cost and considerably reduce developmental risk as potential faults could be found at early stage during the test procedure. It could also eliminate the need of whirl tower test for the rotor regarded as a big burden in the development of rotorcraft. In addition, it had an advantage of testing actual rotor hubs and controls with prop-rotors. As a result, the developmental testing period could be effectively shortened. The measured test data by SUAV GCS and Iron-bird data acquisition system (DAS) showed satisfactory results which meet the developmental specifications of SUAV. Iron-bird testing with SUAV GCS and Iron-bird DAS is shown in Figure13.

Fig.13. Iron-bird Ground Test and GCS

2.4 Flight Test of Full Scale SUAV

Small scale flight demonstrators were developed to prove the flight control algorithm as well as the tilt rotor concept. It successfully flew in helicopter, conversion and airplane modes. The fully autonomous flight including takeoff and landing was demonstrated with dual channeled data link. Figure 14 shows tethering test and free flight test of the 40%-scaled (2m length) flight demonstrator of the SUAV.

Fig.14. Tethering and Free Flight Tests of 40% Small scaled Flight Demonstrator

After confirming the basic flight characteristics of helicopter mode through the tethering test with safety wire, the free flight was executed. The free flight test included three modes of flight. The flight tests were successfully performed at Goheung KARI flight test site. The conversion from rotary mode to fixed wing mode was smoothly executed by following the preprogrammed conversion corridor of flight speed and rotor conversion angle. The gathered data through the free flight tests were implemented to the flight control software of full scaled SUAV. Many valuable information could be obtained with low cost and risk from the free flight test of the unknown tiltrotor configuration. Flight characteristics of stability, controllability and conversion dynamics were obtained through the small scale test.(Fig.15)

4-DOF test to collect the dynamic characteristics data of SUAV was performed before the flight test. After the 4-DOF test, tethering test was performed to evaluate the helicopter mode flight characteristics as shown.

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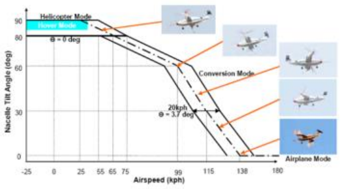

Fig.15. Conversion Corridor of 40% Small scaled Flight Demonstrator

For the tethering test of full scaled SUAV, a tower crane was setup on the flight test site. A safety wire above the airframe for emergency can be seen from Figure 16.

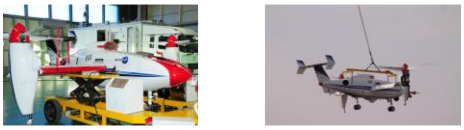

Fig. 16. 4-DOF Ground Test and Tethering Test of full scaled SUAV

Many faults were found during the special ground and tethered tests prior to the flight, which prevented serious accidents that might otherwise have occurred during the flight test. This type of risk control contributed to rapid progress in the conversion flight with a full-scale tiltrotor UAV. A flight involving conversion from helicopter to airplane mode was accomplished within seven months of the maiden flight. (Fig. 17)

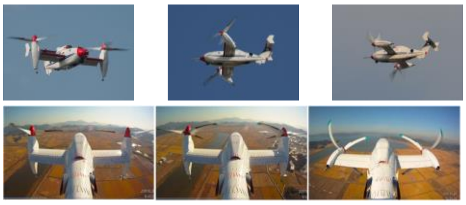

Fig. 17. Flight Test of full scaled SUAV

This smart UAS will be adopted in the Korea Maritime Police and a Korean pelagic fishing vessels company, including the military applications, in the near future. This tiltrotor aircraft is known as the second development success in the world after the V-22 Osprey of Bell Helicopters.[Ref. 1,2,3,4]

3. Drones Development and Operation

3.1 Era of Civil Small UAS and Drones

The era of drones would begin worldwide, when Amazon declares the PrimeAir flight. Recreational drones taking photos in the air were changed to commercial items as door-to-door delivery service. Titan Aerospace, Facebook, and Google would be respectively in the business of high altitude drones, which cruise nearer the edge of the earth's atmosphere and provide technology that could be integral to blanketing the globe in cheap, omnipresent Internet connectivity to help bring remote areas online.

Fig. 18. PrimeAir and Titan Aerospace Drone

Moreover, the conversion of applications from military UAS to civil drones took place. So, various kinds of demand relating flight deregulation of drones have been heading for the aviation authorities. But they have approached step by step about the flight deregulation. For example, in February 2015 Federal Aviation Administration (FAA) in US proposed a framework of regulations that would allow routine use of certain small UAS in today's aviation system, while maintaining flexibility to accommodate future technical innovations: the safety rules for small UAS (under 25kg) conducting non-recreational operations, are as follows; The rule would limit flights to daylight and visual-line-of-sight operations. It also addresses height restrictions, operator certification, optional use of visual observer, aircraft registration and marking, and operational limits.

3.2 Development and Operation Plan of UAS

The national plan of development and operation of the small UAS and drones consists of three different approaches; i.e. UAS system development by industries, UAS core technology study by research institutes, and UVS rule making by aviation authority.

The UAS systems was developed or is under development as follows; Small multi-copter is under development for the safety monitoring and counteraction of people against casualty indoor (less than 6kg) and outdoor (less than 12kg). Medium-sized (less than 25kg) and heavy multi-copter (less than 150kg) were developed for the purpose of door-to-door delivery service, agrochemical spray in agriculture, and reconnaissance & surveillance. Multi-rotor (less than 150kg) will be developed in near future for the reconnaissance & surveillance of Coast Guard. Small (less than 150kg) and medium sized (less than 1,000kg) unmanned helicopter is under development for agrochemical spray in agriculture. Tilt-rotor UAS 150kg TR-60 was developed for various applications such as shoals finding in fishery, nationality identification of ships, and pollution monitoring in the river or the lake. High altitude and long endurance UAS is also under development for the purpose of the reconnaissance & surveillance of Coast Guard, and land, river, lake pollution monitoring, etc..[Fig. 19]

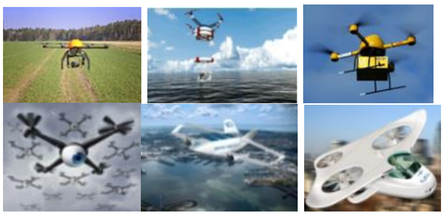

Fig. 19. Various Drones and UAS under development or developed

Core Technology for Unmanned Vehicle System (UVS) is under development with the Government funding. The program aims to support advanced research on unmanned vehicle technologies. The core technologies under studies are as follows.(Fig. 20), and they are expected to be adapted not only to UAV, but also unmanned ground vehicle (UGV), unmanned sea vehicle and unmanned underwater vehicle.

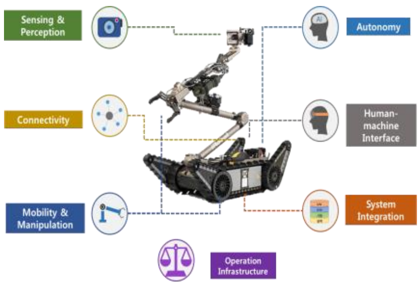

Fig. 20.Core Technologies for Unmanned Vehicle

The Core Technology will be tested and verified by the UAV and UGV cooperation platform. The cooperation platform will consist of 4 UAVs and 2 UGVs with fully autonomous operation. Direct communication between unmanned vehicles will be demonstrated as Figure 21.

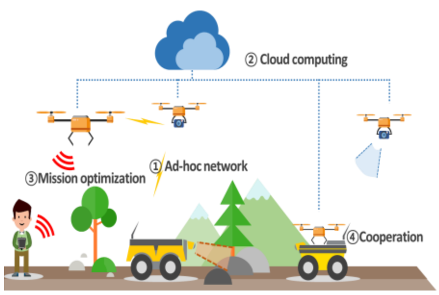

Fig. 21.UAV & UGV Cooperation with Autonomy

UVS rule making by aviation authorities is similar to that of FAA, and also rein reformation of airworthiness is executing by the authority. As the drone’s flight permission rule enacted by FAA was represented previously, the similar rule is applied in Korea. In general, the UAS operation is not limited in case of public safety, disaster relief and emergency countermeasure. The aviation authorities assigned 5 local regions as the regulation free area in which one could fly UVS and drones without aviation permission. The appropriate frequency for the communication of UAS and drones will be chosen, and the UAS regulation will be enacted in near future. [Ref. 5]

4. Summary

The history and situation of civilian Unmanned Aerial Vehicle (UAV) development and operation in Korea was presented. The various UAS terminologies, and UAS and Drones history were described in the part of general introduction. The development process of SUAV was explained in detail including characteristics of tilt-rotor, design and manufacturing, test & evaluation and flight tests. The major features of Smart UAS are illustrated with the developmental history. The future Korean applications of drones and small UAS is presented in detail. Recent situation of civilian drones and UAS is summarized with the viewpoint of their developments and operations. The topics related to UAS regulation and frequency were briefly remarked. The era of UAS and drones looks to be being opened nowadays everywhere.

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