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Design and development of a tilt-wing UAV

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Abstract

In this paper, the mechanical and aerodynamic design, carbon composite production, hierarchical control system design and vertical flight tests of a new unmanned aerial vehicle (UAV), which is capable of VTOL (vertical takeoff and landing) like a helicopter and long range horizontal flight like an airplane, are presented. Real flight tests show that the aerial vehicle can successfully operate in VTOL mode. Kalman filtering is employed to obtain accurate roll and pitch angle estimations.

Key Words: *UAV, quad tilt-wing, VTOL, IMU, Kalman filter*

1. Introduction

There have been significant developments on multi-purpose, compact UAVs in the last years. These vehicles can execute tasks that are either too expensive to be accomplished by human operated vehicles or too dangerous for human life. For this reason, there is an increasing demand for these vehicles in civilian and military applications such as traffic monitoring, border security, inspection of pipelines and powerlines. UAVs are generally classified into two main categories, which are the fixed wing and rotary wing UAVs. Fixed wing UAVs have the advantage of being able to fly at high speeds for long duration with simpler structure. These UAVs have the disadvantage of requiring runway or launcher for takeoff-landing and not being able to hover. On the other hand, rotary wing UAVs have the advantage of being able to hover, takeoff and land vertically with agile maneuvering capability at the expense of high mechanical complexity, low speed and short flight range.

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There are many studies on rotorcraft UAVs with different rotor configurations [1, 2]. Most of them focus on quadrotor UAVs partly due to the stability and efficiency of such platforms compared to helicopter UAVs and partly due to the availability of commercially available off-the-shelf quadrotors [3]. Several groups are working on wide-spread applications consisting of design and control of quadrotor UAVs [4-10]. There are also ongoing studies on tilt-rotor and tilt-wing aerial vehicles combining the advantages of horizontal and vertical flights. Some of these studies are on classical dual-rotor aircrafts like the dual tilt-rotor Bell Eagle Eye [11], Smart UAV of KARI [12], BIROTAN reported by Kendoul et al. [13] and the dual tilt-wing HARVee reported by Dickeson et al. [14]. Among these UAVs, tilt-wing aircrafts, which combine the hovering capability of rotorcrafts and long-range flight capability of fixed-wing aircrafts, are attracting interests of many research groups and industrial companies. Tilting the wing together with the rotor instead of just tilting the rotor provides an increase in the aerodynamic flow over the lifting and control surfaces which is advantageous during transition, and minimizes the lift loss due to downward slipstream in hover [15].

Various sensors such as altimeters, ultrasonic distance sensors, GPS receivers, gyros, accelerometers, pitot tubes (airspeed sensors) and onboard cameras are typically used to provide feedback measurements for the design of stable flight control systems. As the main sensor of the attitude measurement, Inertial Measurement Unit (IMU) contains several sensors like gyros and accelerometers that supply data for the control of the aircraft [16, 17]. However, none of these sensors are capable of providing reliable orientation information under real flight conditions like vibration generated by the rotors and motion of the air vehicle itself. Kalman filter can be utilized to fuse multi-sensor data to acquire reliable flight data under these conditions [18]-[21].

In this work, the design and development of SUAVI (Sabancı University Unmanned Aerial VehIcle) is presented. SUAVI is a quad tilt-wing UAV, which is aimed to operate in surveillance missions like traffic control, border security, and disasters including indoor-outdoor fires, floods, earthquakes etc. The quad tilt-wing structure implies both helicopter-like vertical and airplane-like horizontal flights autonomously. The thrust is generated by four electric motors that are located on the leading edges of the four identical wings at front and rear of the aircraft. The wing-rotor pairs can be tilted from vertical to horizontal position for the transition between flight modes. A hierarchical control system is responsible for fusing all the sensor data and providing the guidance of SUAVI throughout various missions. Furthermore, SUAVI is planned to fly autonomously on a trajectory using its GPS receiver, and whenever necessary it will be directed by a user at the ground station. It will carry onboard cameras both for visual servoing and surveillance applications. Images captured by the wireless camera will be transmitted to the ground station for task decision.

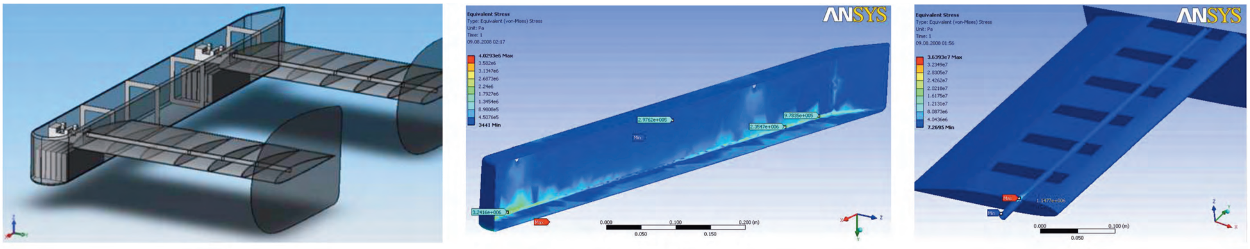
This paper is organized as follows: mechanical and aerodynamic designs, and composite prototype production are presented in Section 2. Hierarchical control system design for SUAVI is detailed in Section 3. Vertical flight experiments are given in Section 4. Finally, the paper is concluded with some remarks along with some future work in Section 5.

2. Design and prototyping of SUAVI

The design of SUAVI is shaped based on the tasks it will perform. It is designed as a compact electric powered air vehicle for both outdoor and indoor applications. It has four tilting wings with the motors mounted on the wings. Thus, the wings occlude the rotor slipstream at the minimum level all the time. The wings are vertical during hovering and vertical takeoff-landing. In this configuration, the rotors produce vertical thrust and steady flight is established using the control on thrusts generated by RPM control of constant pitch propellers. When forward motion is required, the wing angle of attacks are reduced based on the speed requirement and rotor thrusts are adjusted accordingly. For lightness and endurance, SUAVI is produced from carbon composite material. It is planned that this aerial vehicle will perform vertical flight for approximately half an hour and horizontal flight for around one hour in order to perform effective surveillance. Accordingly, the main design specifications of the air vehicle are as follows: 1 m wingspan, 1 m total length and approximately 4 kg weight. A large proportion of this weight belongs to the Li-Po batteries for long flight durations. SUAVI is expected to fly with speed up to 60 km/h in horizontal flight mode.

2.1. Mechanical design

In mechanical design of SUAVI, the main goal is to obtain the most light-weight structure that is capable of withstanding the possible loadings in vertical, horizontal and transition flight modes. To improve the durability in compression loading, which is not the capability of composite materials, usage of sandwich structure on the entire body is preferred. In this sandwich structure, light-weight core material is surrounded by carbon fiber cloth on both sides. The sandwich structure that carries the stresses on the wing surfaces, transmits the generated forces to the wing spars. The spars are planned to be attached to the inner wall of the upper wing surface, providing nearly all stresses on the wings to be in tension. To keep the fuselage stiff against bending and torsion, ribs are installed into the fuselage, so that the distance between walls are preserved (Figure 1.a). At the wing-body joints, single piece Delrin bearing parts are used to prevent bending moment at the wing roots from harming the body sides and to allow the wings to tilt. The batteries, that constitute a very large ratio in the total weight, are placed just below the wing-body joints both to avoid large bending forces at the middle of the fuselage and to increase static stability of SUAVI. Forces that the air vehicle will experience are estimated in simulation environment and mechanical analyses are completed. According to the simulation results, the fuselage is found to be safe up to 8.4 g vertical acceleration, which is also safe for landings (Figure 1.b). The wings are found to be resisting to the worst case air loading, which corresponds to 68 km/h air speed with 10 angle of attack (Figure 1.c).



(a) (b) (c)

Figure 1. Mechanical design of SUAVI (a), stress analysis of the fuselage under 2.5 g vertical acceleration (b), and of the wing for the worst case (c).

2.2. Aerodynamic design

In the aerodynamic design of SUAVI, both aerodynamic efficiency and mechanical features are of interest. The criteria on wing profile decision are that the angle-of-attack is 2-3 with respect to the body at maximum speed and the drag is kept minimum on the entire speed range. Through the utilization of wing profile analysis programs like NASA Foilsim II and JavaFoil, NACA2410 wing profile is decided to be appropriate with 25 cm chord length. An important element in the design is that the lift generated by the rear wings is decreased due to the downwash generated by the front wings, since the rear wings behave as if they have less angle of attack (Figure 2.a). In aerodynamic simulations it is observed that the rear wings have to be placed more than one chord length higher than the front wings to prevent this effect. However, to make the design and production less complicated, the front and rear wings are located at the same vertical level and the rear wings are decided to be used with higher angle of attack. This additional angle of attack ranges from 0 to 15 depending on the flight speed. In order to cease the drag generating trailing vortices at the wing tips, large winglets are installed on the wings (Figure 2.b). These winglets operate by stopping the spanwise flows both on the upper and lower surfaces of the wings. The size of these winglets is near to 15 cm in vertical direction.

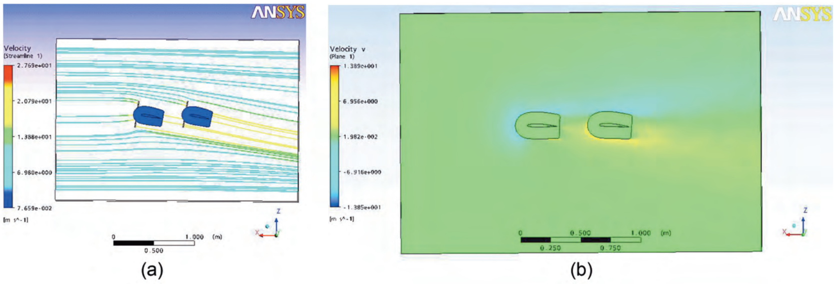


Figure 2. Air flow with downwash of the front wing on the rear wing (a), and spanwise flow speed on the wings with winglets (b).

2.3. Prototyping of the aerial vehicle

The fabrication of the prototype is implemented as a sandwich structured composite in order to fulfill the required strength and weight criteria. As the constituent materials of the sandwich construction, closed cell structured balsa wood is used as the core material and woven fabric carbon-fiber is used as the skin material. The composite parts are fabricated by hand lay-up process on CNC processed molds (Figure 3a, b) and cured by vacuum bagging technique (Figure 3c). Vacuum bagging provides higher fiber to resin ratio than the standard wet lay-up techniques. As a counter mold, vacuum bag ensures the removal of excess resin and a better fiber wet-out [22, 23]. At the end, neat surfaced composite wing and body parts are obtained (Figure 3d, e). The mechanical analysis of the aircraft is performed using ANSYS. The simulation is done under an acceleration of 2.5 g, which resulted in a maximum stress value of 3.2 GPa. The ultimate stress of the composite material is experimentally evaluated as 27 GPa by using a Universal Testing Machine. By assembling composite parts together with rotors (motors and propellers) and landing gears, the first prototype SUAVI is developed as shown in Figure 4.

3. Hierarchical control system design

For the guidance of SUAVI, a hierarchical control system is designed which consists of a high-level controller for decision making, trajectory tracking and visual servoing and a low-level controller for attitude stabilization. As a high level controller, a Gumstix microcomputer (600 MHz ARM Cortex-A8) is used. This microcomputer is responsible for forming the communication link with the ground station and generating the attitude references required for the waypoint navigation. This microcomputer is equipped with a GPS receiver for obtaining

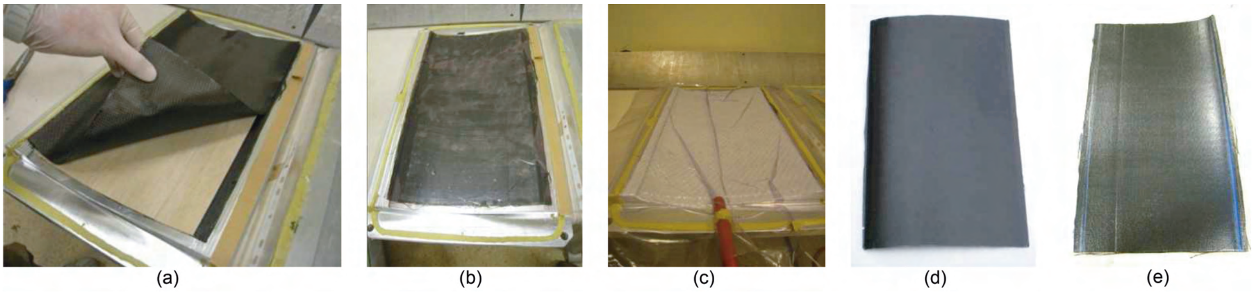


Figure 3. Hand lay-up (a, b) and vacuum bagging (c) processes, and cured upper (d) and lower (e) skins.

Figure 4. Prototype in horizontal (a) and vertical (b) flight mode.

the position of SUAVI and an onboard camera for various visual servoing applications such as vision based landing. Gumstix microcomputer is preferred as the supervisory controller due to its ability to handle complex computations using its DSP processor and Arm Cortex-A8 in a very light-weight and compact structure.

The main goal of the low-level controller is to keep the aircraft at the position and orientation demanded by the high-level controller. To achieve this task, it generates the actuator signals by fusing the flight data obtained from several sensors such as altimeter, sonar, ultrasonic distance sensor, GPS receiver, compass, IMU and pitot tube. For the sensor-actuator integration of SUAVI, two Atmega16 microcontrollers form the low-level controller. One microcontroller is used for handling high-frequency periodic tasks such as obtaining attitude data from IMU and generating actuator signals for following position reference. The other microcontroller is responsible for obtaining aperiodic data from other sensors to be used in the control. Atmega16 has analog-digital conversion and real-time data processing capabilities. An important reason for the choice of this chip has been that it facilitates coding of complex mathematical operations through the C language. The overall structure of the control system is shown in Figure 5. The key point in controlling such an aerial vehicle is to obtain reliable orientation measurements. To achieve the attitude stabilization demanded by the high-level controller, reliable inertial measurements are obtained from a Sparkfun 6-DOF IMU. This IMU is a compact electronic circuit containing 3-axis gyro, 3-axis accelerometer, 3-axis magnetometer and a high-performance microcomputer. In this control system, angular rates measured from 3-axis gyros and angular positions obtained from 3-axis accelerometers are fused in a Kalman filter. One should note that using only gyro integrations to obtain angular position estimation would cause a significant error in angular position data. This error is caused by the accumulation of the integrated value of the gyro drift. In the literature, there are several methods, that rely on using accelerometers as three-axis gravity sensors [17, 19, 20]. However, using only accelerometer data for obtaining angular position estimation would be unstable due to linear accelerations during flight. By applying Kalman filter, the drift in gyro measurements is eliminated using acceleration based angle data. Consequently, reliable roll and pitch angle information are obtained.

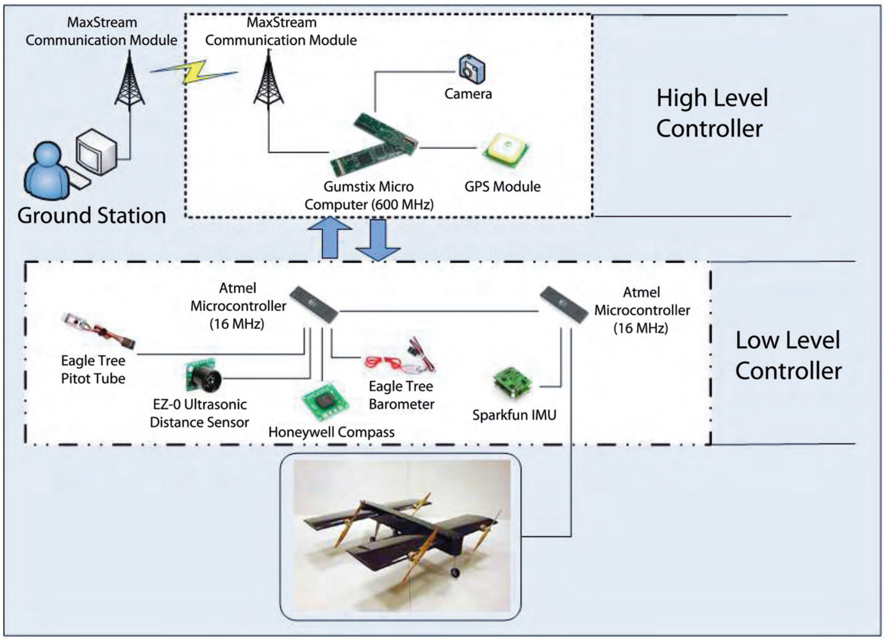


Figure 5. Overall flight control system.

For the initial tests, only the attitude stabilization feature of the control system is activated. The attitude references are fed in to the system by a pilot via RC receiver. The block diagram of the low-level controller structure with the RC receiver can be seen in Figure 6. This circuit captures the roll, pitch, yaw and motor thrust references from the RC receiver and angular position estimations and angular rates from IMU. It then calculates control signals of each motor, feeding them to motor drivers using servo pulses. To prevent the noise due to the high current in motor drivers, the circuit is electrically isolated from the motor drivers and servos using optocouplers.

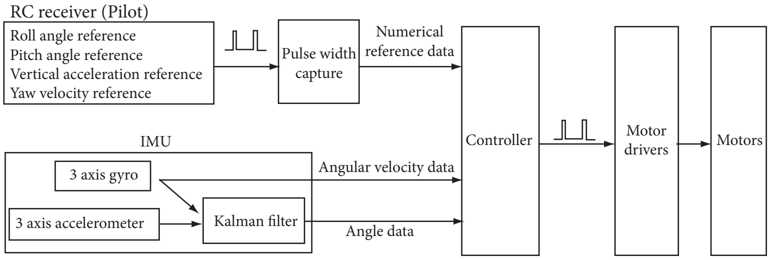
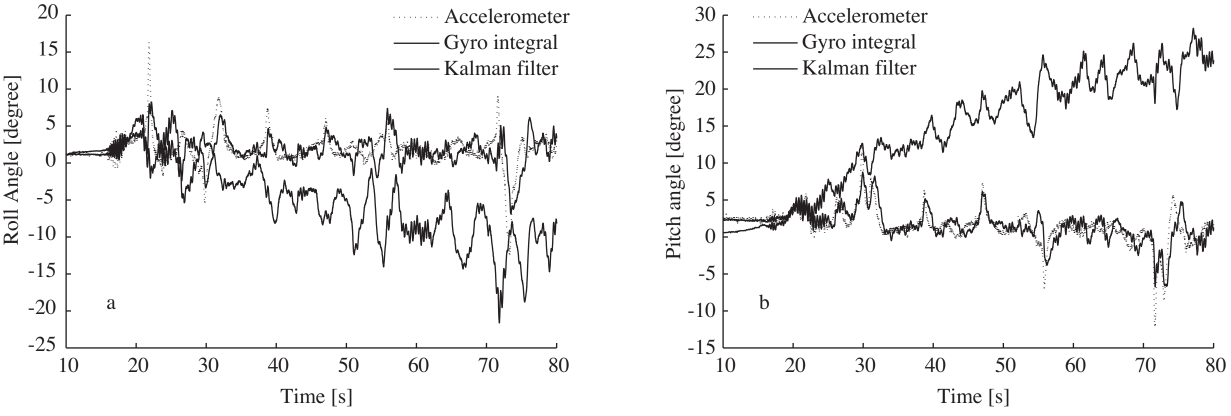


Figure 6. The block diagram of the low-level stabilization.

4. Vertical flight experiments

With the developed flight control system successful vertical flight tests have been realized. Initially, a gravity compensated PD controller is used. During the vertical flight experiments, the composite prototype stably took-off with small operator corrections, stably hovered for a while and then smoothly landed. Gyro drifts are compensated by a Kalman filter using the data obtained from accelerometer. Estimated roll and pitch angles by Kalman filter can be seen in Figure 7. Note that estimated angles by Kalman filter and accelerometer measurements are close to each other while the angles obtained by integration of gyro outputs significantly drift. Note also that spikes in the accelerometer readings are eliminated by Kalman filter. Snapshots from the flight test are given in Figure 8 respectively.



(a) (b)

Figure 7. Estimation of roll (a) and pitch (b) angles by Kalman filtering.

Figure 8. SUAVI in vertical flight tests.

5. Conclusion and future work

Design and development of a new quad tilt-wing aerial vehicle (SUAVI) is presented. In particular, the mechanical and aerodynamic design are detailed, and carbon composite production is explained. The sensor and actuator system integration is described. By applying analog filtering to the measurements obtained from IMU for eliminating noise and by utilizing Kalman filter for compensating gyro drifts, reliable attitude information is obtained. A gravity compensated PD controller is successfully implemented in vertical flight tests where stable vertical flights are achieved.

As a future work, the prototype will be optimized and both vertical and horizontal flights will be realized using sensors such as GPS and onboard cameras.

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