UAS DESIGN REQUIREMENTS FOR OPERATION IN COLOMBIAN MOUNTAIN ENVIRONMENTS

Luis B. Gutiérrez*, Omar Hazbón*, and Björn Appel**
***Universidad Pontificia Bolivariana, **Technische Universität Berlin**
luis.gutierrez@upb.edu.co;omar.hazbon@upb.edu.co;bjoern.appel@tu-berlin.de

Keywords: *UAS, GNC, UAV, Aircraft Design, UAS Market*

Abstract

This paper describes the state of the art of UAS technology in Colombia, its potential applications and the design requirements and challenges for a UAS capable of operating in the tropical mountain environments common in this country.

A review of research capabilities and manufacturing institutions that could support UAS developments is deeply analyze as well as the position of the government and industry against this technology.

1 Introduction

Colombia completes then years of operations and research in UAS technology; however this time hasn't been enough to consolidate a UAS industry and its deployment. Although there's the need from industry and military organizations to incorporate these systems in their operations, foreign technology cost has mined the intensions from these institutions. Local research organizations had made an effort to develop this technology at a lower cost, but the lack of support from government and industry has made the progress very slow.

Through the last ten years, military institutions have determined to buy developed technology or work by its own, but not to support current third-party developments. On the other hand, industry has determined to hire different UAS mission services and not to incorporate this technology in its operations. In addition, airworthiness authorities are not committed in developing or complying with existent UAS regulations restricting the operations within the Colombian airspace.

This paper will analyze the changes in research strategy and marketing that must be done before UAS technology can mature in Colombia as well as the opportunities available to foreign companies.

2 UAS Technology in Colombia

UAS technology had gained attention of both governmental & private institutions. The Colombian Air Force - FAC has employed Boeing´s ScanEagle UAS to assist the Army and Navy in counter-terrorism and counter-narcotics operations for the last 6 years. Other UAS´s has been tested in several military operations around the country; this is the case of General Ceramic's Silver Fox.

FAC also tried to develop its own UAS´s. The first fixed wing project consists in the development of a small low–cost and short range autonomous surveillance system. The development included the air vehicle, autopilot and ground control station. This task was assigned to the Science and Technology division at CAMAN, air force base in Madrid-Cundinamarca and the project was designated as ANT 001 which stands for Unmanned Aerial Vehicle 001 and shown in Fig. 1. The system should have the option to carry a laser target designator in addition to the EO and IR cameras. The developed airframe has the typical configuration of a 4m span model aircraft trainer: high wing, conventional empennage and a frontal tractor propulsion system. The balsa and plywood airframe is covered with a polyethylene film to protect the wood from engine emissions and atmospheric conditions. The propulsion system consists in a two stroke, 5.7 hp Fuji BT- 64EIS gasoline engine driving a Zinger propeller with 24 inches in diameter and 12 inches of geometric pitch. The payload capacity of this platform will be 5 kg and the endurance of no more than 30 minutes. The team successfully developed a telemetry system and video transmission to the ground control station, however autonomous flight was not achieved. The test flights were performed as a remotely piloted vehicle. The original design was modified to achieve a lighter airframe and better takeoff and climb performance using a powerful engine. The improved design was called the ANT 002 which features composite airframe and a propulsion system consisting of a two stroke, 7 hp Fuji BT- 86EI opposed twin gasoline engine driving a Zinger propeller with 22 inches in diameter and 8 inches of geometric pitch, but again, no autonomous flight was achieved.

Fig. 1. ANT 001 UAS prototype.

A second and parallel UAS project was established with the objective of detecting antipersonnel mines from the air. The development task was assigned to CITA research group at EMAVI air force base in Cali - Valle del Cauca. The team acquired an Autocopter and planned the development of a payload with particular sensors so antipersonnel mines could be detected from the air. After several crashes during the fly training the project was abandoned. Fig. 2 shows FAC's Autocopter UAS.

Fig. 2. Autocopter [1]

A recent FAC project is called IRIS. The aim of this project is to develop a recognizance and surveillance UAS capable of delivering weapons. The project was assigned to CIAC, an aircraft maintenance company owned by FAC and private share holders which is manufacturing aircraft trainers. CIAC divided the development tasks as follows: The aircraft will be designed in a company called Aeroprof and manufactured by a second company called Aerocompuestos. The autopilot, communications and ground control station will be selected from a third party foreign company. The fixed wing prototype has a span of 10 and a length of 7.8 meters respectively. It has a pusher Rotax 912 engine at the propulsion system and double tail boom configuration. The aircraft weights 1100 lbs and has been designed for 20 hour endurance. The System currently lacks of an autopilot, communication system and ground control station. IRIS prototype is shown in Fig. 3.

Fig. 3. CIAC's IRIS UAS [2]

University of Cauca has been working for several years in the development of guidance, navigation and control systems.

Several model aircrafts were manufactured to test these devices but no proof of autonomous flight its known. Some of the designed models include Efigenia EJ-1B Mozart, Efigenia EJ-2A Fatima and Efigenia EJ-2B Maria as shown in Fig. 4.

Fig. 4. Efigenia EJ-1B Mozart (above) and Efigenia EJ-2B Maria (below) [3]

San Buenaventura University started their research in autonomous UAS's with the Navigator X-3 project. The short range air vehicle was designed to perform Intelligence, surveillance and reconnaissance missions. The aircraft wing spans 5 meters and its fuselage length is 3.3 meters. The wing area accounts for 3.54 square meters and the maximum takeoff weight is 490 Newton. The aircraft was designed to meet performance parameters such as a range of 360 km, a cruise speed of 90 km/hour and a payload of 100 N. However these performance parameters have not been reached due to a lack of an electric generator. The takeoff distance requirement established by the designers was 100 meters at an altitude of 3000 meters above sea level, for these reasons the design features two 58 cubic centimeters two stroke engines combining tractor and pusher configuration as shown in Fig. 5. The airframe consists in a combination of composite and wooden materials. The aircraft incorporates Micropilot's MP2028^{g} autopilot and the communication system consists in a data and video link. The ground control station is a portable laptop with a directional antenna. Flight test was done manually by radio control and autonomous flights are on schedule.

Fig. 5. San Buenaventura Navigator X-2 UAS [4]

The UAS Jaguar shown in Fig. 6. was the result of a project initiated by a company called TELSAT in cooperation with the School of Aeronautical Engineering at Universidad Pontificia Bolivariana – UPB back in 2006. The mission objective was to perform surveillance. The development tasks were divided as follows: TELSAT was in charge of financing and manufacturing the prototype; UPB will cover the cost and carry out the design of the aircraft. The selected autopilot was the MP2028^{g} from Micropilot and communication systems were provided by Microhard. Aircraft conceptual design, detailed aerodynamic calculations and wind tunnel tests of the lifting surfaces were performed at UPB facilities. The designed prototype has a wing span of 6 meters, a length of 5 meters, a 17 horse power DA gasoline engine and a MTOW of 40 kg. TELSAT manufactured a prototype but no flight test was done. The company tried to establish a contract with FAC prior to continue with the investment but the efforts were unsuccessful.

Fig. 6. UPB´s CAD render (above) and TELSAT prototype (below) of Jaguar UAS.

UPB University has been involved in UAV projects since 2004. The idea of developing an autonomous unmanned aerial system started when the electric power transmission company ISA (acronym which stands for Interconexión Eléctrica S.A.) contacted UPB to develop an automatic power line inspection system for its infrastructure. UPB and ISA with the support of Colciencias setup a project to develop an autonomous robotic device provided with high resolution cameras that will search for damages at tower structures, foundations and cables. The development included the control system and its hardware. The project was divided in three stages: the first will be the analysis of the best technology to solve the problem and a conceptual design of the system including a deep cost analysis of the complete development, the second stage was the detailed design of the system and the third stage the manufacturing and test of three prototypes. The outcome of the first stage was the selection of an autonomous UAS called AURA and its conceptual design exposed the following characteristics: wing span: 10 meters, wing area 9 square meters, wing aspect ratio 11, length 7 meters, 81 hp reciprocating four stroke twin cylinder engine and a 1.68 kw electric generator. Other systems include a parachute and airbags for recovery. The concept performance features a maximum take-off weight of 500 kg, a payload weight of 50 kg, a range of 400 km, an endurance of 5 hr, a rate of climb of 305 m/s, a maximum ceiling of 6000 m, a cruise speed of 205 km/hr and a stall speed of 110 km/hr. The payload consists of a FLIR Systems high resolution electro-optical camera. A first approach to the autopilot architecture (sensors integration and flight computer) was also designed and a prototype of the electronic hardware was developed as depicted in Fig. 7.

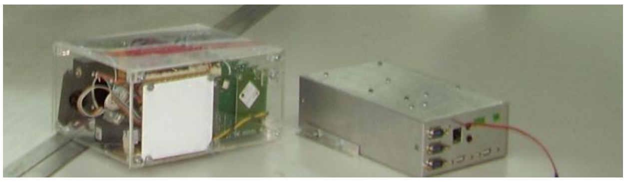

Fig. 7. AURA’s sensors (left) and flight computer (right).

To show the company a low cost working prototype, a remotely piloted scale vehicle called “AURA Jr.” was manufactured and the concept was tested as shown in Fig. 8. After completing the first development stage ISA decided not to continue with the project because they were not convinced that the technology will satisfy their inspection needs.

UPB setup its own UAS project based in the knowledge gained with the ISA experience. The scope of this project was to fully develop the guidance, navigation and control system that was initiated during the AURA project and improve the Aura Jr. flying platform with the aim of performing autonomous flight test. Two sets of computational tools were developed during the design of this system. The first computational tool consists of a series of Matlab routines that performs aerodynamic,

Fig. 8. AURA CAD model (above), AURA JR (Below).

performance, dynamic stability and stress analysis of the complete flying platform. The second computational tool is useful for the development of guidance, navigation, and control algorithms. Flight simulation of the UAS missions is possible with data provided by the previous tools. It was possible to obtain a considerable reduction in the autopilot size and the aircraft geometry was modified to optimize its performance. The new UAS was named "Condor Andíno" (Fig. 9. And Fig. 10.) and two air vehicles were manufactured. Radio control flight test were successfully carried out. The guidance, navigation and control software was coded and current development focuses on autopilot new hardware integration and de development of the ground control station.

Fig. 9. Cóndor Andíno UAS CAD model.

Fig. 10. Cóndor Andíno Prototype.

3 UAS Potential Applications in Colombia

Potential UAS technology applications in Colombia cover civil and military tasks. Starting with civil applications lets recall that the country is located at the equator and as a consequence it is subjected to tropical storms, high temperatures at low altitude regions and low temperatures at high altitude terrains. The Andes mountain range splits in three branches when it enters the country at the southwest, offering high altitude navigation obstacles like Colon, Nevado del Huila and Ritacuba Blanco peaks that reach 5.775, 5.750 and 5.330 meters above sea level respectively. Surrounding territories of previous peaks are not an exception because they are located at 4500 meters above sea level. The rest of the territory consists in low altitude valleys, Jungle and flat lands. The geography of the country is then diversified so aircrafts can be flying at sea level and then being forced to climb at high altitudes to follow the contour of the terrain.

As a consequence of climate changes, the tropical storms are increasing in duration and intensity and severe damages in the country´s infrastructure and disasters are happening. Mountains slides are damaging roads, electricity transmission infrastructure and hydrocarbon pipelines. Dams are also being broken and floods in lower territories are causing millionaire loses. These damages are not caused instantly so companies are looking for a new technology that can inspect their infrastructure with certain frequency and act on time to prevent the disaster. UAS technology can be a practical solution for these types of inspections without risking human lives. The main companies that require these services are: ISA, Ecopetrol, Cerrejón, Cormagdalena and INVIAS.

Construction companies are currently hiring aerial photography services that use manned aircrafts and small remote controlled aircrafts for this job. The Agustin Codazzi Institute will benefit from UAS technology in its, vulcanologic and glacier monitoring as well in its cartography airborne manned missions.

UAS technology can be an invaluable tool for institutions like the Civil Defense and Red Cross that perform search and rescue missions at the jungle, high altitude territories and glaciers. Flying at low speed at territories above 4.500 meters or glaciers is avoided by manned recognizance aircraft and in some cases forbidden by airworthiness authorities due to the low visibility and performance at this altitude.

UAS´s can be designed to fly at this conditions without the limitations previously described.

The internal and geopolitical conflict in Colombia defines broad military applications for UAS technology. Border and territorial waters both at the Atlantic and the pacific constantly are being patrolled mainly to detect drug traffic. The armed forces need this type of technology to combat paramilitary groups in missions like communication relays, target designators, intelligence and surveillance. Recently there's an interest from the air force to equip UAS with weapon delivery systems. Possible clients apart from FAC are the army, navy and police aviation.

4 UAS Market in Colombia

At present no UAS fabricated in Colombia has been commercialized. Some small businesses have been created to offer aerial photography and video services for different applications including events monitoring, publicity, architecture, and civil engineering. Colombian armed forces have had great interest in using UAS technologies, and they have been using it since 2005. Some big companies have showed their interest to use UAS technology for the inspection of their infrastructure. However there has been some reluctance in the government and the armed forces to support private research projects in this topic.

In 2005 Colombian Air Force bought AutoCopter UAV to test the UAS technology for the protection of Air Force Bases. In 2006 the USA government donated a set of the ScanEagle UAS for operations against drug traffic and the guerrillas [5] and they have been using them since then. They have also deployed the Silver Fox UAV for some operation tests [6,7]. It seems that the Armed Forces from Colombia have negotiated or are negotiating the purchase of a bigger UAS with Israeli company [8,9]. They are also undertaken a project with CIAC and some private experts to develop the UAS IRIS [10,11].

Nowadays the number of companies recently established to provide aerial photography and video services with small UASs is growing, in some cases the vehicles are integrated by them; in other cases the equipment is imported. Some of these companies are:

- Electrosoftware with UAV HeliCam libélula geográfica, [12].
- Air Photo with UAVs Draganflyer X6 produced by Draganfly Innovations Inc. [13].
- Cámara del aire [14].
- Perspectiva Aérea with UAVs HeliCam [15].
- Advector [16].

It is known that there are requirements from big energy transportation companies like Interconexión Eléctrica S.A. E.S.P (ISA), and oil companies like ECOPETROL to use UAS technology for the maintenance inspection of the power lines and pipelines infrastructure. For all these kind of operation an UAV with a beyond line-of-sight opportunity is necessary. Even though some tests have been performed it seems that the huge costs imposed by foreign companies have prevented the widespread use of this technology in Colombia. That is why at present there is an open market for low cost and effective UAS technology developed locally.

Jane´s information group predicted in 2010 an UAS Market for Colombia of USD$324,000 Million for the period 2010 -2019 as shown in Fig. 11.

5 Challenges in UAS Design for Colombian Mountain Environments

All UASs have to operate in low and high altitudes, low and high temperatures and high humidity in Colombia. These conditions have a great impact on the aerodynamic and structural design of an UAV. A good climb and descent

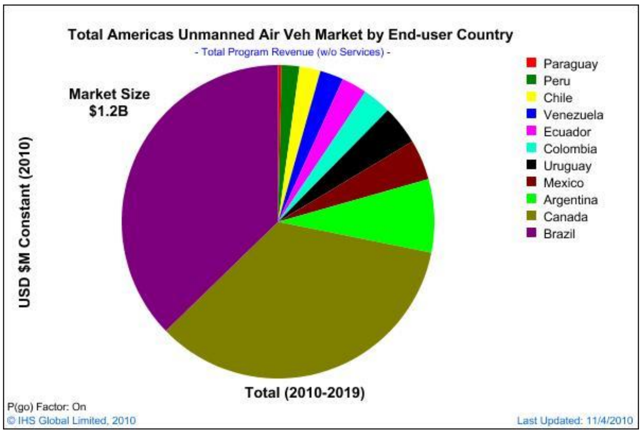

Fig. 11. Total America´s UAS market. [17]

performance is required to follow the terrain contour for infrastructure inspection but in the condition to maintain the required obstacle clearance. It has been shown by FAC that high humidity also damages the UAS electronics especially during operations in the jungle.

Small propulsion systems are subjected to a considerably loss of power with altitude. It will benefit the development of small turbochargers to maintain the sea level take-off and climb performance when operating at high altitudes. Fuel consumption will be kept at the lowest possible value if there's no need to increase the size of the engine for a particular type of mission.

Nowadays manned missions are carried out only during the day. There is a need to cover missions at night in emergency situations. The unmanned character of this technology enables the accomplishment of night missions without risking the integrity of human lives. It is required a high level of autonomy in the UAS so it can be operated easily for non-expert personnel without the need of extensive and expensive training. Payload requirements to accomplish the missions include daylight/IR cameras, LIDAR (Laser Imaging Detection and Ranging) and special communication equipment for long range communications like satcom datalinks.

The definitions for all kinds of unmanned aircraft operation are the same published by ICAO. Under ICAO an unmanned vehicle (UAV) can be defined as Remotely-piloted aircraft system (RPAS) or Remotely-piloted aircraft (RPA). All ICAO standards are affected by unmanned aircraft operations. The classification based on the operation of an unmanned vehicle is more helpful for the analysis. The ICAO classifies based on the visual and radio line-of-sight. All operation within a line-of-sight defines as Visual Line-of-Sight Operation (VLOS) and Radio Line-of-Sight Operation (RLOS). The most challenge full operations are beyond line-of-sight and are defined as Beyond Visual line-of-sight operation (BVLOS) and Beyond Radio line-of-sight operation (BVLOS) [18].

6 Operational Requirements for Tropical, High Altitude and Mountain Environments

The operation requirements for UAV are very similar to the ICAO Annex 6 Operation requirements. The requirements include flight preparation, performance operation limitations and fuel management in normal and abnormal situations. Especially for the flight preparation all weather and terrain conditions which impact the safety of a flight have to be considered. Any fuel calculation includes a flight to the destination and to an alternate airport if necessary. For safety aspects a fuel reserve has to be added to comply with unexpected events. For all operation beyond the line-of-sight some additional requirements are necessary to comply with engine failures, loss of data link, loss of control, failure of navigation and airframe damage. The special weather and geography condition of Colombia have a great impact on UAV operations.

Colombia is situated in the Intertropical Convergence Zone (ITCZ) and the geography is characterized by the Andes and the Amazon rainforest region. Therefore all earth climate zones with their special weather phenomena can be reached in few hours. All these conditions have to be considered for a safe UAS operation.

Due low altitude operation during observation flight the weather conditions and terrain situation have to be analyzed carefully for every flight. For flight preparation the aviation community is using forecasts (upper wind temperature, Significant Weather Charts SIGMETs, AIRMETS etc.) which are provided

by the World Area Forecast System (WAFS) [19] to avoid dangerous weather conditions (e.g. tropic thunderstorms, mountain waves, heavy rain, etc.). [20] For low altitude operation in mountainous areas a good and precise weather model and forecast system is necessary to prepare and operate safely in Colombia [21]. By combining a 4D flight plan and a 4D weather cubes an optimal and safe flight route can be determined [22].
The terrain has to be analyzed to maintain a safe obstacle clearance during normal and abnormal situations (e.g. engine failure, loss of data link, failure of navigation etc.). All possible scenarios have to be considered during the procedure developing phase. Various digital terrain models with different resolutions can be used in MATLAB for this analysis process. For a first estimations a 30 arc seconds resolution (approx., 1km) like the GTOP30 model can be used. [23] For a detailed analysis it is necessary to use models with higher resolution like the 2 arc seconds resolution model (approx. 30m) of the Shuttle Radar Topography Mission (SRTM). [24] This model can be used in MATLAB or in Google Earth to determine areas where the climb performance of the UAV is smaller than the terrain gradient which results in a dangerous obstacle clearance and in a violation of minimum flight altitudes (ICAO Annex 2).

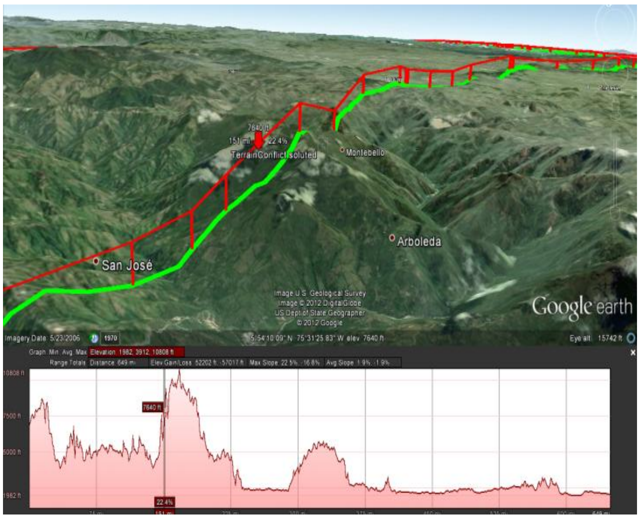

Fig. 12. Analysis of a low altitude observation flight by using Google Earth and MATLAB. The vertical terrain contour reaches altitudes from 500ft until 10.000 ft.

7 Development of a UAS Complying with Colombian Needs

At Universidad Pontificia Bolivariana a UAS is being developed to cope with the difficult conditions of tropical high altitude mountain environments found in countries like Colombia. The development of this UAS has been faced integrally considering aspects of aeronautical design for optimal performance in these environments, development of proprietary algorithms for guidance, navigation and control of the UAS, development of proprietary hardware for integration of all the electronic components including CPU, sensors, servo actuators, data links, electro optical system, video transmitter, generator and power supply systems with battery backup.

7.1 Design of a UAS for Colombian Needs

The aeronautical design of the UAS was composed of three stages: first, a conceptual design was performed as the first approximation taking into account the mission requirements; second, an optimized performance-based design of the aircraft was performed using our own software tools; and third, the detailed design was performed taking into account the maximum load requirements calculated in the previous stage.

For the performance based optimized design, proprietary software tools were developed to accomplish the following tasks:

- A model of the propulsion system was developed including the engine and propeller model. These models were used to optimize the propulsion system selecting an appropriate engine propeller pair for the requirements of the mission performed by the UAS. Especial emphases were placed in take-off and climb performance at high altitude tropical environments.
- The aerodynamic model of the whole aircraft was approximated. An approximate modeling method was developed based on a modification of lifting line theory that allows using experimental airfoil aerodynamic

coefficients data, and predicting nonlinear behaviors like stall. The method allows determining the aerodynamic coefficients of the whole aircraft based on its airspeed, angle of attack, sideslip angle, angular rates, and control surfaces positions. To do this, a nonlinear least squares algorithm was used to solve the nonlinear system of equations resulting from the same conditions used in lifting line theory for each lifting surface (wings and stabilizers). Then the results are combined for all the lifting surfaces using their relative positions to get the total force and moment coefficients for the whole aircraft. The aerodynamic model was used in conjunction with the propulsion system model to construct the simulation model for the whole aircraft. The model was completed with the mass and inertial matrix properties which were estimated based on the CAD model of the whole aircraft.

- A complete analysis of the aircraft performance was carried out based on the nonlinear model obtained before. To do this a software was developed to calculate precisely the performance characteristics under different flight conditions based on the whole nonlinear aircraft model instead of using traditional textbook formulas.
- The aircraft model was used to calculate static and dynamic stability and control characteristics of the aircraft to guarantee good handling qualities for the design.
- The method described before for the aerodynamic modeling of the whole aircraft allowed also calculating the aerodynamic loads on the structure of the aircraft. Later these loads were used for the stress analysis of the structure to guarantee the integrity during any flight condition.

All these steps were carried out iteratively doing small corrections to the design parameters until the specifications were appropriately fulfilled. The initial geometry and weight of the aircraft used in this optimization process was taken from previous conceptual design. When all the performance requirements were satisfied by the design, the iteration was stopped, following the detailed design of all components of the UAS.

The design of the UAS was performed using the software described before, looking for a UAS with small take off distance and good climb performance characteristics. The design obtained was the Andean Condor UAS, see Fig. 13. The specifications for this UAS are:

Wing span 5.1m
Length 2.5m
MTOW 25kg
Payload 5kg
Endurance 4h
Stall speed 40kph
Max speed 140kph
Climb rate 2000ft/min
Ceiling 15000ft
Engine Power 5.7HP

Fig. 13. Andean condor UAS

7.2 UAS guidance, navigation and control

Instead of buying a commercial autopilot for a small UAV, it was decided to develop the guidance, navigation and control system of the aircraft. The main reason for this was to create a guidance, navigation and control (GNC) system very flexible in terms of hardware and software to facilitate the implementation of different kinds of UAS, not only the one referred in this paper, but also other types like rotary wing systems. With this decision the technology dependency of our development is minimized and the software and hardware is customized to exploit the design characteristics of the UAS. This also enables the easy integration of new and advanced algorithms into the flight control system, and the change of any sensor or the inclusion of other sensors for the GNC subsystem.

For a UAS operating in tropical high altitude mountain environment is very critical to have a very precise GNC system. It is important that the system considers the topographical characteristics of the terrain including a precise elevation model, since a small deviation of position could result in very abrupt changes on terrain elevation. The guidance system should consider the elevation model for planning the trajectories of the UAV, maintaining a minimum above ground level (AGL). The navigation system should be able to estimate precisely the position and velocity of the aircraft with available sensor information in an autonomous way. The flight control system should be able to control the aircraft through all flight conditions, following the commands from the guidance system given the feedback provided by the navigation system. Next, these systems implemented for the Andean Condor UAS are described in more detail to show how they guarantee the precision required by the application.

7.2.1 Navigation system

The navigation system estimates position and velocity of the aircraft based on the information provided by onboard sensors. Used sensors are: inertial measurement unit (IMU) with three axis accelerometers and three axis gyros; three axis magnetometer; a GPS receiver; a barometric altimeter; and a sonar altimeter. The navigation system uses a 16 state Extended Kalman Filter to estimate position, velocity, attitude quaternion, accelerometers and gyros bias every 10ms. An accurate gravity model has been included to avoid the necessity of estimating gravity. To improve the accuracy of the navigation system for the UAS application requirements in mountain environments, special care has been taken in the calibration of all sensors. For this purpose particular calibration algorithms have been developed to calibrate the IMU, the magnetometer, and the barometric altimeter. IMU is calibrated for alignment and bias errors (accelerometers and gyros), magnetometer is calibrated for soft iron and hard iron distortions. Barometric altimeter is calibrated for each mission based on true altitude, pressure, and temperature reference values; this calibration is normally repeated in flight for maintaining altitude accuracy. Furthermore, the aircraft is fitted with a pitot tube and sensors of angle of attack and sideslip so these values are also made available to the flight control system.

7.2.2 Guidance system

For most commercial small UAV autopilots, the guidance system provides automatic waypoint navigation. The guidance system implemented in Andean Condor UAV goes a step further giving a higher level of intelligence to the system. The guidance system was designed to guarantee that the trajectories followed by the UAS comply with the performance limits of the UAV in each phase of flight, and also limit the trajectories to guarantee a minimum AGL based on the digital elevation model for the region where the UAS is operating. Each phase of flight is composed of a list of low level waypoints, and a set of performance limits. Each low level waypoint can be executed in different modes: pass through, cut, loiter, hold on, pass though until a specified minimum speed is reached, pass though until a specified maximum speed is reached, pass though until a specified minimum altitude is reached, and pass though until a specified maximum altitude is reached. In each phase of flight the guidance system imposes maximum and minimum limits to the trajectories in terms of altitude, rate of climb and descent, air speed, and turn rate. The guidance system incorporates several phases of flight: standing, taxi, take-off, initial climb, en route, holding, approach, landing, abort take-off, abort approach, and abort landing.

The guidance system can be operated in manual or automatic modes. In automatic mode, instead of just giving low level waypoint data to the guidance system, higher level information is provided through the high level command interface making sure that each phase of flight is executed properly within performance limits of the aircraft. In manual mode, guidance is executed based on a joystick, but the guidance system guarantees that commands provided to the flight control system are within performance limits like in automatic mode. In this case the guidance system detects automatically the phase of flight in which the UAS is flying. The guidance system is completely configurable so the mission can be programmed before flight, and can be modified at any time in flight through the command interface.

7.2.3 Flight Control System

The aircraft nonlinear model previously developed was also incorporated in the software to simulate the aircraft and to design and test the aircraft flight control system. In addition to the development of a complete nonlinear model of the aircraft, parameter identification methods have been implemented so the model can be improved in the future based on actual flight data [25].

For the design of the flight control system three alternatives have been implemented:

- Multi-loop PID controller with iterative feedback tuning algorithm. The PID loops incorporate saturations with anti-windup to fulfill limits required in each phase of flight. Longitudinal control is achieved with three PID loops: one air speed PID and two PID connected in cascade structure with angle of attack PID inner loop and altitude PID outer loop. Lateral control is accomplished with three PID loops: one sideslip PID and two PID loops connected in cascade with roll PID inner loop and heading PID outer loop. A novel iterative feedback tuning algorithm was developed to optimize the tuning of these PID loops based on the nonlinear model obtained before for the UAS [26]. The method optimizes a quadratic performance target function using the closed loop response obtained from simulations. In this case the characteristics of the model are not used directly in the controller tuning process, but in simulations and in some other numeric manipulations. The optimization process is made using a modified version of the Levenberg-Marquardt algorithm.
- Robust gain-scheduled H_∞ control [27]. In this scheme a polytopic approximation of the linearization family of the nonlinear model is used for the design. Because the linearization family in the operating region derives in a linear parameter varying (LPV) description with a nonlinear dependence of a set of parameters, a least squares approximation of the system matrices is used in order to obtain affine dependence. The polytopic description is obtained from the affine LPV model when the operating range is defined choosing the varying parameter inside a convex hull. The controller is synthesized using the Bounded Real Lemma in order to guarantee quadratic H_∞ performance over the operating region.
- Gain scheduled H2 control [28].

These flight control alternatives have been successfully tested in simulation with the complete nonlinear model of the aircraft [29].

7.2.4 Software infrastructure for GNC systems

A very flexible software infrastructure was developed to implement GNC system which expedites the development process. The development of this infrastructure has taken a big effort, but this facilitates future developments and modifications of the designs. This infrastructure allows the designer and user of the UAS to implement the software incorporating with no major effort a series of useful capabilities and services, just following some simple rules in the design of the software. Another advantage of using this infrastructure is that all the application data is placed in a well-organized tree structure, which allows the access to all the information for configuration, monitoring, logging, communications, etc. The software infrastructure provides a command interface server that allows several authenticated clients to connect to the software and perform diverse tasks using an extensible command language interactively, with scripting capabilities. The command interface allows to execute diverse commands, for instance: basic commands that enable navigation through all data tree; basic commands to monitor data, set data, and change units for all the variables; basic commands for configuring the data logging capabilities, save data, and send data through the data link in a programmable manner; other command extensions programmed in the application. The infrastructure allows executing scripts, facilitating tasks like mission planning, sensor calibration, and flight control configuration and UAS monitoring. The ground control station uses the same software infrastructure giving more flexibility of all the components.

All of these features make the software for the UAS GNC system more flexible and easy to customize for the UAS application.

7.2.4 GNC hardware implementation

The GNC system and payload control are composed of the control software described before; the hardware allowing the implementation of the software, interfacing with sensors, actuators and communication data links; and hardware for generator, power supply and battery backup. A block diagram of this hardware is shown in Fig. 2.

7.3 UAS communication system

Colombian mountain environments impose big challenges for the UAS communication system. To minimize the communication requirements of the UAS, the system was designed for maximum autonomy. That is why the Andean Condor UAS does not require the communication system to operate all the time. The software infrastructure includes a command server not requiring the communication link to be connected all the time. When a command needs to be sent to the UAV, client software in the ground control station establishes a connection with the server through a communication link. Telemetry data are always broadcasted by the UAV and those data can be received by the any ground control station able to decode it. To guarantee the privacy of the communication with the UAV, the

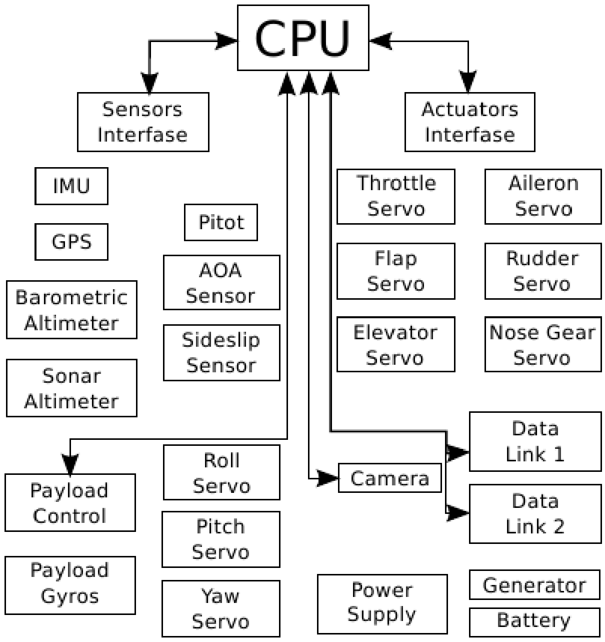

Fig. 14. Hardware block diagram for Andean Condor UAS

information is encrypted using a key just known by the server in the UAS and the client in the ground control station.

Several options are considered for the UAS communication system data links:

- UHF spread spectrum wireless modem. This kind of modem commonly operates in the 900 MHz band, with a range up to 100km with line of sight, and usually can be operated in a network configuration to increase the range.
- Cellular wireless modems can be used to communicate wherever a cellular infrastructure is available, which is common for many places where the UAS operates. This kind of communication link offers a low cost high bandwidth communication link.
- Satellite modems are other possibility for communication links in remote regions. This kind of communication increases the operation costs bur is required when no other possibility is available.

Video information can be transmitted using the same communication link used for data communication, if the bandwidth requirement is not so high, but in some cases uses a dedicated link based on any of the alternatives already discussed.

7.4 UAS payload

The payload for the UAS usually consists of an electro optical system (video camera) or an IR video camera. In any case it is important to have a gyro stabilized platform to mount the sensor to have good quality stabilized images. That is why a gyro stabilized platform was developed for the Andean Condor UAS, see Fig. 15.

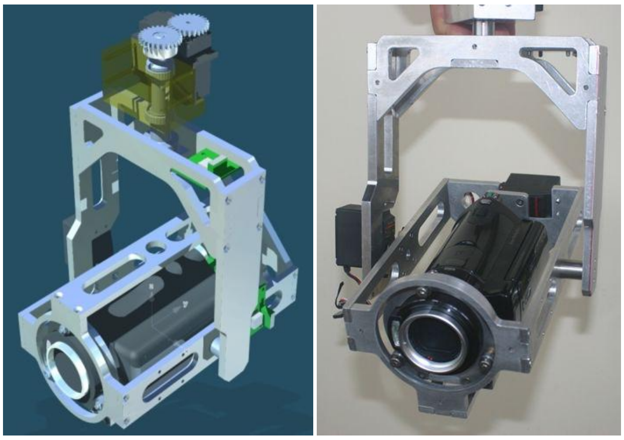

Fig. 15. Gyro stabilized platform CAD model and Prototype for Andean Condor UAS

Control software for this platform implements control algorithms to keep the camera pointing in one direction regardless of the attitude of the UAS. The controller uses information processed by the UAS navigation system to know the attitude of the platform base and feedback from three gyros mounted in the platform to help in the stabilization process. This capability combined with careful trajectory planning of the UAS, enables it to capture good video information of a fixed or moving target. Gyro stabilized platform software is integrated with the GNC software onboard UAS, allowing the use of the same command interface software used by the GNC system to control the payload.

8 Conclusions

Colombia requires UAS technology for the current industrial and military needs. Foreign technology is too expensive to acquire and operate; in addition some foreign technology is not suitable for the local operational environment.

Colombian research and manufacturing organizations have the capacity to develop the technology required to fulfill the industrial and military needs, but economic support from the government and industry is required. In addition, Colombian airworthiness authority (AEROCIVIL) must regulate UAS design, manufacturing and operations in a proactive way so the technology implementation is not obstructed.

Foreign UAS companies can cooperate with these local research and manufacturing institutions to reduce the cost of their products and adapt their models to the Colombian environment. Investors can think in supporting current UAS projects based in the market forecast and together innovate in this novel technology by beating these new challenges.

References

[1] *Douglas Hernández 2006, UAV-Autocopter-01, viewed 20 June 2012, <http://www.fuerzasmilitares.org>*

[2] jamobr 2012, *Corporación de la Industria Aeronáutica -CIAC-* , Web no oficial de las fuerzas militares de Colombia, viewed 17 june 2012, < http://www.foro.unffmm.com/>

[3] Cordoba M. 2012. viewed 20 may 2012, <http://www.efigenia-aerospace.com/us_index.htm>

[4] Escobar J. 2011, *Design & Development of First Colombian Short-Range Unmanned Aerial Vehicle for Intelligence, Surveillance, and Reconnaissance*, AUVSI, viewed 12 April 2012 <http://www.symposium.auvsi.org/auvsi11/public/SessionDetails.aspx?SessionId=308>

[5] "Aeronaves no tripuladas en Colombia: el ScanEagle," November 2011, [http://www.webinfomil.com/2011/12/aeronaves-no-tripuladas-en-colombia-el.html]

[6] Mulligan, A, "Update on Silver Fox UAV Programs and Operations," October 2007, [http://www.acrtucson.com/Presentations_n_Publications/pdf/Mulligan_ACR_UAS_DC_October10th_Presentation.pdf]

[7] Aponte, R., "Silver Fox in South America," *SBIR in Rapid Transition 2007*, Washington D.C., October2007, [http://www.zyn.com/sbtcevents/rt072/presentations/Aponte.pdf]
[8] "Colombia contará con un UAV Hermes 900 de Elbit Systems para misiones de seguridad fronteriza," January 2012, [http://www.infodefensa.com/?noticia=colombia-contara-con-un-uav-hermes-900-de-elbit-systems-para-misiones-de-seguridad-fronteriza-2&categoria=uavs]
[9] "Colombia habría comprado avión no tripulado a firma Israelí," January 2012, [http://www.canalrcnmsn.com/noticias/colombia_habr%C3%AD_comprado_avi%C3%B3n_no_tripulado_firma_israel%C3%AD?page=1]
[10] "Noticias RCN conoció el modelo del avión de combate no tripulado de fabricación colombiana," January 2012, [http://www.canalrcnmsn.com/noticias/noticias_rcn_conoci%C3%B3_el_modelo_del_avi%C3%B3n_de_combate_no_tripulado_de_fabricaci%C3%B3n_colombiana]
[11] "Primer vuelo de prueba del UAV táctico colombiano 'Iris'," November 2011, [http://poderiomilitar-jesus.blogspot.com/2011/11/primer-vuelo-de-prueba-del-uav-tactico.html]
[12] Electrosoftware, visited June 2012, [http://www.electrosoftware.net/pag/helicam.php]
[13] Air Photo, visited June 2012, [http://www.airphotocolombia.com/index.html]
[14] Cámara del aire, visited June 2012, [http://www.camaradelaire.com/index.php]
[15] Perspectiva aérea, visited June 2012, [http://www.perspectivaaerea.com.co/]
[16] Advector, visited June 2012, [http://www.advector.co/index.html]
[17] Jane's DS forecasts 2010, viewed 17 November 2010.
[18] ICAO**.** *Meteorological Service for International Air Navigation*. 15th edition, ICAO, 2004.
[19] Flight Safety Foundation. Killers in Aviation: FSF Task Force presents facts about approach-and-landing and controlled-flight-into-terrain accidents. Flight Safety Digest, Vol. 17, No. 11-12, pp 1-257, 1998.
[20] http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/GTOPO30
[21] http://vterrain.org/Elevation/SRTM/
[22] ICAO**.** *Manual on Remotely Piloted Aircraft Systems (RPAS)*. 1st Edition Draft, April 2012.
[23] Sharman, Robert, Semi-empirical methods for the prediction of mountain wave turbulence (MWT), *ARAM*, Los Angeles, 2011
[24] Knapp, David, et al, A Weather Decision aid for unmanned aerial vehicle missions, *12th ARAM*
[25] Ortiz V., P. A. *Modelo matemático para un vehículo aéreo no tripulado de ala fija usando métodos de identificación paramétrica*, Master Thesis, Universidad Pontificia Bolivariana, July 2007.
[26] Ramirez, J. A., Gutierrez, L. B. and Vasquez, R. E., An iterative feedback tunning scheme for the multiloop PID control of a UAV, *ASME 2010 International Mechanical Engineering Congress & Exposition*, Vancouver, BC, Canadá, November 12-18, 2010.
[27] Ramirez, J. A., Gutierrez, L. B. and Vasquez, R. E., Robust gain-scheduled control of a UAV based on a polytopic model approximation, *ASME 2010 International Mechanical Engineering Congress & Exposition*, Vancouver, BC, Canadá, November 12-18, 2010.
[28] Ramirez, J. A., *Diseño del control de vuelo para un vehículo aéreo no tripulado de ala fija*, Master Thesis, Universidad Pontificia Bolivariana, June 2010.

Copyright Statement