29th Congress of the International Council of the Aeronautical Sciences
St. Petersburg, Russia; September 7-12, 2014

DEVELOPMENT OF A MULTI-PURPOSE UAV WITH BIO-INSPIRED FEATURES

Rodrigo Kuntz Rangel*,, Karl Heinz Kienitz*, and Mauricio Pazini Brandão***
***Technological Institute of Aeronautics, ** BRV – UAV & Flight Systems / BRVANT**

Keywords: *Small size UAV, COTS systems integration, Bio-inspired UAV system*

Abstract

This paper describes the development of a small sized UAV[1] (Unmanned Aerial Vehicle) system, called Bio-UAV, with some features of biological inspiration in flying animals. The developed system allows the operator to remotely fly and control an aircraft from a ground station. The aircraft is a small sized UAV, equipped with an embedded telemetry system, and a group of embedded gyroscopes and inertial systems that work in conjunction with servomotors, in order to provide the automatic or manual aircraft stabilization, control, and navigation in any atmospheric condition. The ground station is composed of a laptop computer equipped with interfaces, joysticks, virtual reality helmet (compounded by LCD displays and gyroscopic sensors), and special devices which provide real time acquisition of image and telemetry data on board the aircraft. By means of the specific software installed in the ground station, the aircraft and its associated systems can be constantly controlled and monitored. The ground station software makes real time comparisons between the aircraft actual route and its predefined mission route. In case it proves necessary, the software can command corrections of the aircraft route. As additional feature, a dedicated Head-Up-Display (HUD) with aural warning features is added, making use of virtual reality glasses which allow complete pilot immersion into the navigation system. This paper, of multidisciplinary character, describes the development of the mini-UAV system with three bio-inspired features: a line-of-horizon-based computer vision procedure to determine the vehicle's attitude that is used for stabilization (imitating birds), a bio-ecolocalization feature used for aircraft landing (imitating bats), and a bio-inspired navigation algorithm with sun heading estimation. The described development illustrates the viability of combining aeronautical requirements and low-cost, COTS[2] hardware to develop UAV systems with bio-inspired navigation and control subsystems. The result is a state-of-the-art mini-UAV (in terms of small size and bio-inspiration) for possible use in civilian and military applications.

[1] Unmanned Aerial Vehicle, MTOW below 5 kg
[2] Commercial Off-The-Shelf (COTS)

1 Introduction

The beginning of the UAV concept dates back to the American Civil War, when contenders tried to launch balloons with explosive devices to fall on enemy ammunition depots. During World War II the USA used an UAV prototype in the so-called Operation Aphrodite. The prototype was a manned airplane in unmanned mode. During the Cold War, several UAV have been developed. In the 1960s, drones have been used extensively in reconnaissance missions in Vietnam.

Over the years, with the development and optimization of electronic equipment, new generations of aerial robots have been created, mainly for military applications. With the end of the Cold War, UAV slowly found their way into commercial applications as agriculture, surveillance, power line inspection, communication relay etc.

In face of the actual economic scenario, it is very important to optimize and to reduce the cost of processes and equipment. This entails a strong interest in affordable tools that can help the pilot, the crew, or the passenger to use airborne equipment in the easiest possible way.

The main objective of the work described herein is the development of a low-cost and multipurpose portable electrical UAV system ([1] [2]) with bio-inspired features [13], that can be used in applications such as tactical surveillance, power line inspection, aerial mapping and so on.

The scope here is a fixed wing UAV flown remotely by the operator with some bio-inspired features as auxiliary input to the avionics systems. The related bio-inspired features are incorporated via the avionics system. These features are three: a line-of-horizon-based procedure to determine the vehicle's attitude, which is used for stabilization (imitating birds), a bio-ecolocalization feature used for aircraft landing (imitating bats), and a bio-inspired navigation algorithm with sun heading estimation. The described development illustrates the viability of combining aeronautical requirements with low-cost and COTS hardware to develop UAV systems with bio-inspired navigation and control subsystems. The result is a state-of-the-art UAV (in terms of small size and bio-inspiration) for possible use in civilian and military applications.

In the development of complex multi-purpose and highly flexible UAV systems, the applications requirements are very strict. In some cases, the UAV shall be portable to be stored in a military bag, the noise produced by the engine shall be as low as possible, the take-off shall be done by manual procedure and the landing shall be done on short fields. The avionics shall be compact, lightweight, and easy to operate by a soldier during a tactical mission patrol. Depending on mission scope, this equipment will be used just once. This demands low-cost yet functional equipment.

The same set of requirements will enable the UAV system to be used in nonmilitary applications, such as power line inspections or urban surveillance. In this work, we will not describe the possible applications, but the benefits of a low-cost system for them.

Considering civilian applications, the UAV will fly over cities, critical structures, and areas with high population density. Thus, the UAV design, in terms of weight, size, noise, materials, and mission envelope, shall be very flexible in order to adapt the aircraft to the application scope.

The avionics may be considered for use in manned aircraft after the proper certification by aeronautical authorities. Such certification process is complex; it is governed by directives such as RTCA[3] DO-160, that defines physical aspects of equipment installation in aircraft, and RTCA DO-178, that defines software issues, or STANAG[4] 4671, Unmanned Aerial Vehicle Systems Airworthiness.

2 Development

2.1 System Overview

Here we describe the development of a multipurpose portable electrical UAV system, with bio-inspired features, composed of aircraft, ground station (Command and Control (C2) Station), and field support equipment. This UAV can be used in applications such as tactical surveillance, power line inspection, aerial mapping etc.

The developed system allows the operator to remotely fly and control the aircraft from a one-man portable ground station. The aircraft is an electric small sized high wing UAV, pusher configuration, with wing span of 47 inch, 2.5 lbs of weight, flight autonomy of 40 minutes, cruise speed of 70 km/h, and maximum speed of 96 km/h, called Bio-UAV. The UAV design uses a modular concept. The bio-inspired features have been applied in the design of the aircraft and of the related avionics systems.

The operator can assemble and disassemble the wing, tail and fuselage in order to store the UAV in a portable bag that can be carried by a single person. The airborne subsystem is composed of an encrypted telemetry system, a GPS receiver, specific sensors, and dedicated electronic boards for all equipment and sensors system integration functions.

For concept demonstration purposes, the bio-inspired features, the attitude estimator for stabilization, the bio-ecolocalization for aircraft landing, and the navigation algorithm with sun heading estimation, will be used as auxiliary features, in some cases replacing the conventional equipment, such as GPS and gyroscopes.

The ground station is a one-man portable design, composed of a laptop computer equipped with interfaces, joysticks, Helmet Mounted Display (HMD), and special devices which provide real time acquisition of image and telemetry data coming from the aircraft. By means of specific software installed in the ground station, the aircraft and its associated subsystems can be constantly controlled and monitored. The ground station software makes real time comparisons between the aircraft actual route and its mission predefined route. In case it proves necessary, the software can command corrections onto the aircraft route. As additional feature, a dedicated Head-Up-Display (HUD) with aural warning features is created and shown through the virtual reality glasses, allowing a complete pilot immersion into the navigation system.

2.2 Aircraft (Bio-UAV)

The Bio-UAV, displayed in Figure 1, is a complete man-portable UAV system developed by the first author ([3] [4]). It operates either in fully radio-controlled mode from a ground station, or with some level of autonomy. The aircraft is of modular conception with bio-inspired design [13] for simple maintenance, replacement of components, and flight performance. The airframe is made of carbon fiber, light wood and EPP foam. The configuration has an electric pusher engine to allow for unobstructed installation of sensors in the nose, like a video camera (flight camera). The high-wing configuration with a big wing span reduces power consumption, load weight, and favors a stable flight as a trainer aircraft ([5] [6]).

[3] Radio Technical Commission for Aeronautics
[4] Standardization Agreement

Fig. 1. Bio-UAV, Electric UAV prototype.

The fuselage is strong and lightweight, with ample compartments for systems installation and payload packaging. The total aircraft weight (aircraft and sensors) is around 2.5 lbs. The aerodynamic design of the Bio-UAV has been inspired on a falcon. Table 1 shows the relation of weight, wing area and wing load of both.

Tab. 1. Falcon and Bio-UAV data

Type	Weight (gf)	Wing area (cm^2)	Wing load (gf/cm^2)
Falcon	1,225.5	1,342	0.91
Bio-UAV	1,200.0	2,400	0.70

An electric powered engine assures flight durations up to 40 minutes. Typical operating altitudes lie between 20 and 2,000 feet above the local terrain, with a typical cruising speed of 60 km/h and an operational speed range between 25 and 96 km/h. This range allows the aircraft use in missions which require slow flight, like aerial photography and power lines inspection, as well as in missions that require a stable platform with quick response and speed, like convoy following.

In order to guarantee the reliability and redundancy of the controls and mission equipment, the electronic equipment are split into two groups, one group comprising the aircraft basic controls and the other group including the aircraft mission equipment.

The aircraft basic control group of electronic equipment keeps the aircraft stabilized through the deflection of the primary flight controls (pitch, roll, and yaw axes) and throttle control. The primary flight surfaces are commanded by servo-engines connected directly onto each surface.

The mission group of electronic equipment is responsible for mission payload, like video-camera, telemetry link, and their integration. The Global Positioning System (GPS) and Inertial Measurement System Unit board (IMU) are used in both groups. Basically, the airborne system allows the operator to remotely fly and control the aircraft and its systems through a ground station.

The aircraft's main mission is to follow the trajectory previously created by the navigation software. Necessary sensors to accomplish this are installed onboard the aircraft. GPS is used to determine the current aircraft position and speed, IMU to obtain information on aircraft attitude, video-link to display flight images in real time to the pilot etc. The bio-inspired sensors shall be used directly to replace the GPS, with the sun heading estimation feature, or the IMU, with line-of-horizon based on computer vision, or as auxiliary devices, when necessary.

In the present work we consider the same methodology used on UAV designs presented at the IEEE Aerospace Conferences 2009-2014 ([4] [14]). We have used COTS equipment to build the avionics systems, like GPS, IMU, sonar, data-link telemetry boards, and RX Control Module (RX-CM). The system integration is fundamental to allow the communications between these equipment and sensors.

In this work, proper interfacing, nominated integration box, has been developed. The interfacing device is a dedicated micro-processed board. Considering a modular design, it is possible to upgrade the avionics architecture in order to install or remove each sensor to adapt the avionics systems to the aircraft mission. In some cases, the connection between two integration boxes may be necessary to change the number of sensors.

Considering that the Bio-UAV prototype is a totally electronic UAV, without a gas engine, a speed control unit is required to control the electrical engine. The speed control is a PWM (Pulse Width Modulation) controller which converts the command signals from RX-CM (low amperes), increasing or decreasing the RPM, allowing the UAV control in terms of speed variation. The speed control input signal is provided by RX-CM. The electrical engine is a brushless 12 VDC @ 20 A DC engine.

As described in [13], the integration box manages the connection and the communication of airborne equipment in real time. Inside the Bio-UAV aircraft there are a set of sensors (GPS, IMU, sonar, sun heading estimator, camera) and boards (telemetry link and RX-CM - a command and control receiver that converts flight commands, from a regular Radio Controlled (RC) equipment into PWM signals for servo-engines) to be interfaced, all connected to the integration box ([7] [8]).

In general, GPS and IMU provide the aircraft position, speed, altitude, and attitude information to the integration box, which manages (it creates data packets) and forwards it to avionics subsystems and to the telemetry link (including the RX-CM). From there, information is sent to the ground station.

The bio-inspired sun heading estimator is used to give to the UAV an estimated heading, based on sun position, used in situations without a GPS navigation system. The bio-inspired line-of-horizon based on computer vision procedure uses the flight camera to acquire flight images. This procedure represents the bird´s eyes. The sonar sensor is used as a bio-ecolocalization feature for aircraft landing (imitating bats).

In the ground station, all received data from the UAV are compared with the mission plan and displayed to the pilot through a dedicated graphical interface. The current aircraft position and the planed mission position are shown, and then the pilot can control the aircraft's route to correct its status by sending commands to the Autopilot.

The video link with the flight camera provides the ground station on board in real time with flight imagery from the UAV.

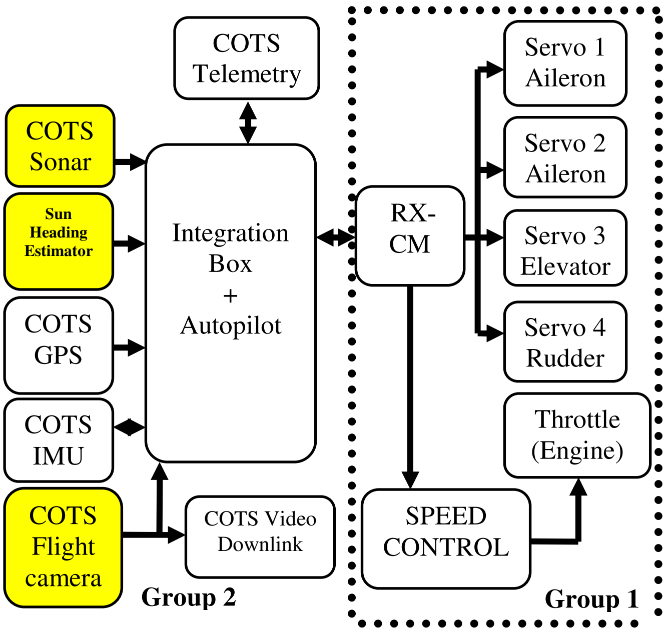

Fig. 2. Bio-UAV airborne equipment integration diagram.

Figure 2 shows the Bio-UAV airborne equipment integration diagram.

2.3 Ground Station

To support the UAV mission, the ground station is a component of vital importance. It is responsible for acquiring all aircraft captured information, according to the features described in the following paragraphs, as well as to ensure the aircraft's take-off and landing processes, which are performed manually. The station has a modular design. It is portable, easy to transport, and provides operational agility in the field, embedded in a vessel or interconnected to a fixed control system, which can be on the ground, sea surface, or in the air.

Through the ground station, the UAV can be remotely controlled. Specific software on the station laptop enables the creation of specific missions, uploading and downloading aircraft data. It also allows the use of flight controls (joysticks) and shows an interface with Moving-map / Synthetic Vision software. It creates a complete navigation system via waypoints and an interface containing visual and audible navigation (easy to understand) instructions similar to current HUD and avionics systems used in modern aircraft [9].

Using a special helmet fitted with a set of LCD screens, speakers, and gyroscopes, along with HUD graphical interface and aural warnings from the navigation software, a full integration between the pilot and the aircraft can be reached. Flight audio and video are captured and recorded, processed in real time, and displayed to the pilot visually and through sound. This creates a virtual cockpit for the UAV remote pilot, allowing total immersion in the aircraft virtual cockpit ([4] [9]). Considering other command stations and software modules, external devices shall be considered to customize the mission application, through LAN, WLAN over the Internet, using point-to-point or satellite data communication.

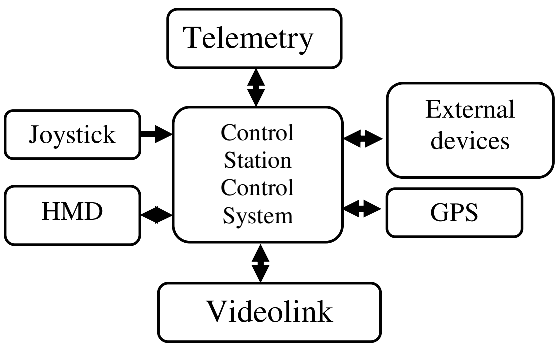

Fig. 3. Ground station basic diagram.

Figure 3 shows the ground station basic diagram.

The operational range, in terms of aircraft control in manual mode, depends upon the radio control range. Considering applications where there is the need for extended manual control (amplified Radio Frequency (RF)), there are systemic provisions for using satellite communication equipment.

The main focus of the ground station on board software, namely, the navigation and control software, is the integration of equipment used in the UAV system. The navigation is supported by GPS, stabilized gyros or bio-inspired features and internal procedures of the navigation software.

The navigation system uses GPS [7] or the sun heading estimator to determine the aircraft position, the mini inertial system or the bio-inspired attitude estimator to determine aircraft attitude, and control laws set through the internal working logic ([2] [13]). Information is acquired and compared every second to mission path parameters and terrain data base information previously obtained from 3D navigation charts. All information is processed and the current position is displayed to the pilot.

All hardware devices attached to the laptop computer are controlled by the navigation software. An external data file is loaded with the mission information plan by the navigation software. This software can manage the acquisition of mission and telemetry data, perform aircraft position and navigation calculations ([2] [4]), present the results of the calculations in a graphic interface, manage the video images from the aircraft, and build the visual and graphic interface to the user in real time.

The additional modules of navigation and control software represent the specific software to their mission.

The navigation software has been developed using Microsoft Visual C++ [7]. The functional software diagram can be seen in Figure 4. This design is based on modules, where each additional function is separated from the main software. In some cases, one module may even be in a different program.

Fig. 4. Navigation and control software, functional diagram.

The flight and mission software layout, as well as the displays available to the pilot in the ground station are shown in Figure 5.

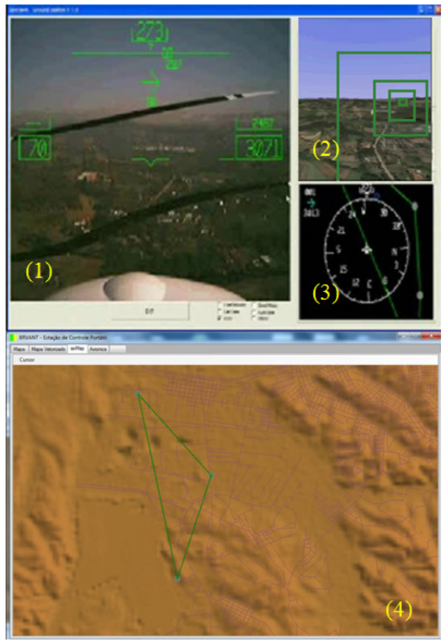

Fig. 5. Flight and mission software layout.
(1) Flight View
(2) Synthetic View
(3) Mission Path and AIS
(4) Mission map (geotagged based)

2.4 Bio-inspired features

The bio-inspired features represent some biological abilities of the animals under study in a quantifiable manner, relying mainly on birds and bats. These features are the result of state-of-the-art development of small sized UAV systems started in 2005 by Rangel et al. ([2], [3], [4], [13], and [14]).

By convention, the qualification Bio-Inspired Feature is applicable to all systemic functions based in biological systems. In this paper the following three bio-inspired features are considered:

- Line-of-horizon-based computer vision procedure to determine the vehicle's attitude and used for vehicle stabilization (imitating birds),
- Bio-ecolocalization feature used for aircraft landing (imitating bats) and,
- Bio-inspired navigation algorithm with sun heading estimation (imitating long-range migrating birds).

As essential premise for the development of bio-inspired features, all conventional sensors (GPS, IMU) and classic controllers, such as PID, are supposed unavailable. However, for a comparative validation of the results, flight tests are performed changing the onboard setups, between classic setup (using GPS, IMU, and PID) and non-classic (using bio-inspired features and non-classic controllers). In both cases, the aerial platform is the same.

After the tests, considering a comparative analysis between settings, it has been possible to survey characteristics of both forms of control, the classic and the non-classic ([10][16]).

The computational models (algorithms), still under development, are the simplest possible in terms of processing demand. Initially, the bio-inspired functions (modules) have been designed to be installed and processed in the ground station and, after the validation, embedded in the aircraft. The non-classic controller in study has been based on artificial neural networks (ANN, the MLP algorithm has been used for learning by back-propagation) and on expert systems (based on decision rules, as described in [16], [11], and [12]).

Through the bio-inspired features, we intend to obtain a functional model that dispenses the use of conventional sensors for aircraft stabilization, navigation and landing, which will reduce costs and simplify further embedded systems. Biological features are useful in environments whose characteristics are apprehended using the animal's sensory abilities, which enable it to react and adapt to its habitats. The features themselves are characterized by the application of skills acquired in the environment, i.e., skills like hunting, avoiding obstacles and the flight itself.

The learning process from parents to offspring observed in nature is critical to the composition of bio-inspired styles. For the implementation of a bio-inspired feature, a learning process stage is used to obtain knowledge of the respective model of the feature. Figure 6 shows the learning process diagram used herein to obtain knowledge of the respective model.

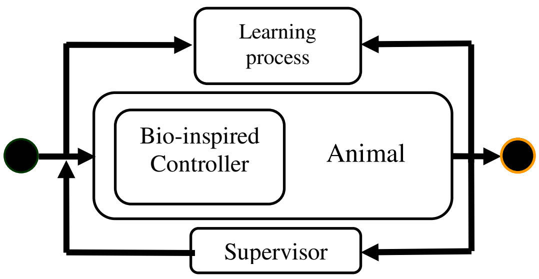

Fig. 6. Bio-inspired learning process diagram.

Line-of-Horizon (Attitude)

The first bio-inspired feature developed here is the Line-of-Horizon (attitude estimator), using a computer vision system allied to a bio-inspired vision model, in order to be able to determine the aircraft attitude and, thereafter, use this determination to aid in the aircraft stabilization. Instead of using stabilization devices based on conventional technologies such as micro-processed stabilizers and inertial systems, the development in this work has been linked to initially identify the attitude of the aircraft and, after, its stabilization, having birds as source of inspiration.

As demonstrated by zoological studies, the birds are animals best adapted to flying. The nature over the years perfected their body and sensory systems, making them true flying machines.

The bio-inspired line-of-horizon with stabilizer computational model used in this research is shown in Figure 7.

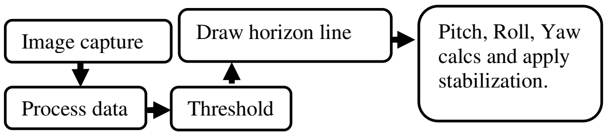

Fig. 7. Bio-inspired line-of-horizon with stabilizer, computational model.

The Bio-UAV fixed reference system model can be observed in [15]. Considering this reference system definition, the next step is to identify what or where the axes are affected for each bio-inspired style. In the bio-inspired aircraft stabilization system the related axis are considered corresponding to pitch (X) and yaw (Y), as well the angles θ and φ, respectively.

According to the diagram shown in Figure 7, this bio-inspired module comprises the following steps:

1. to capture flight images in real time,
2. to apply the predominant color of the filter (bio-inspired algorithm),
3. to find the threshold between the sky and the water or soil,
4. to draw the midline threshold between sky and water or soil and,
5. to calculate φ, θ, and ψ of X, Y, and Z axes angles, and apply the method of stabilization.

The angle ψ describes the aircraft yaw motion. Its calculation is produced by obtaining the heading of the aircraft.

The images are captured via the flight camera installed in the aircraft nose. Subsequently, the images are pre-processed, where appropriate filters, according to the predominant color desired, are applied. After this pre-processing phase, an image with color based on the filter dominant color is obtained and the threshold between the sky and the water or soil is determined.

This threshold is obtained by acquiring a set of samples from the analysis of the pixels histogram that make up each picture map. The sky, water, and soil patterns are defined at the model time calibration. Once obtained the threshold, a straight line is drawn between the set of samples, the line-of-horizon.

To obtain a known reference, a second line is drawn on the image. This line represents the system origin point angular reference, that is, the initial system calibration. By comparing the lines, one representing the system initial calibration and the other the horizon, it is possible to obtain the angular variation of the aircraft X and Y axes to the horizon, and determine its attitude.

Figure 8 shows the bio-inspired line-of-horizon process.

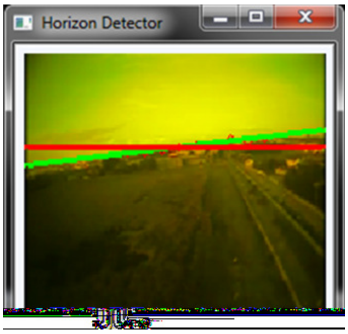

Fig. 8. Bio-inspired line-of-horizon process.

After obtaining the φ and θ angles, the next step is to attempt stabilizing the aircraft using non-classic controllers [16].

Bio-eco-localization Landing Procedure

The second bio-inspired model developed in this work is used to assist the UAV during landing. This model is based on bats eco-localization and will be used to define the distance between the aircraft over the ground during the landing approach.

According to the zoological studies, it has been observed that bats have a sense of perceived distance and location of objects in the environment (prey, objects etc.), using this ability for navigation and hunting [17]. For the development of bio-ecolocalization, a pointing down COTS sonar device has been installed at the aircraft bottom. The bio-inspired algorithm manages the sonar intervals of ultrasound in accordance with the biological profile used by bats.

The computational model developed for the bio-inspired landing system is analogous to the bio-inspired line-of-horizon with stabilization one, with the addition of a specific model for the aircraft envelope correction, shown in Figure 9.

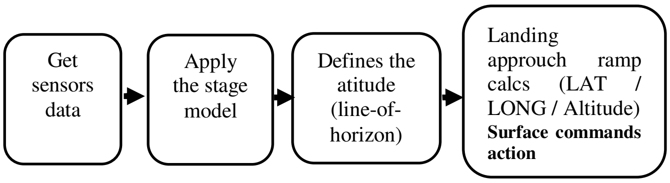

Fig. 9. Bio-inspired computational model diagram, ecolocalization (landing procedure).

This bio-inspired model uses the previous line-of-horizon with stabilization model to define the aircraft attitude, in order to set the pitch, roll, and yaw angles according to the landing conditions. Additionally, the model acquires the flight data in order to define the ideal path through mathematical and logical parameters which are used for subsequent encoding of the computational tools. This model comprises the following steps:

1. to capture data from the sonar,
2. to apply related bio-inspired model (algorithm),
3. to trace the average distance (altitude),
4. to calculate the approach ramp, and
5. to define aircraft adjustments (surface controls).

The avionics system captures data from the sonar installed onboard the aircraft. It interprets and processes the signals according to the functioning logic of the bio-inspired computational algorithms. According to the landing stages depicted in Figure 10, the period between pulses is varied according to steps 1, 2, or 3, as suggested by the operating mechanism of the biological model (bat) and fully discussed in [13].

The average altitude is calculated excluding the two most extreme measurements. With the average elevation between the UAV and the ground defined, other factors are considered to complement the landing process, such as speed, descent rate (climb), geographical position, and UAV attitude.

When the UAV starts the final approach procedure (last stage), a table containing the information necessary to calculate the ideal landing ramp is loaded into the computer model. All involved variables are set according to the table database. The pitch angle, speed and descent rate are varied according to their stage in order to keep the aircraft on the ramp and to respect the ideal operating envelope.

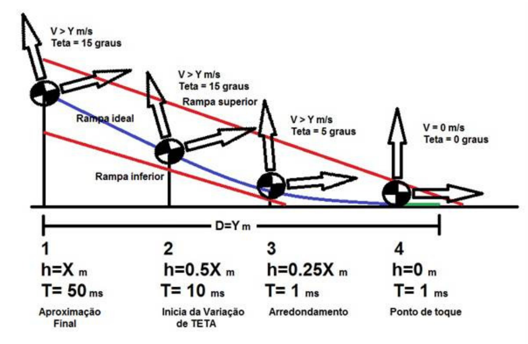

Fig. 10. Bio-inspired landing process.

Sun Heading Estimator Navigation Procedure

According to [16], migrations refer to regular and predictable displacements between two regions, characterized by reproductive (in summer) and non-reproductive (in winter) regions. The interest in such natural phenomena is to understand how birds define the direction of displacement, i.e. what is the heading to be followed. Studies show that some climate factors contribute to migration, such as the length of a day in certain region. Pough [17] and Rangel [13] show that in spring season, the migration displacement points towards the north induced by the increase in the length of the day.

This bio-inspired model is an auxiliary device that provides to the Bio-UAV navigation system a bio-inspired sun heading estimator, and the use of a sensor type capable of providing the magnetic heading indication during the flight.

Physically this sensor consists of an array of four LDR (Light Dependent Resistor) mechanically arranged symmetrically in a circle with 360 degrees. Each LRD covers 90 degrees, represents a quadrant, and is connected electronically to a microcontroller system. This system is able to read and decode the analog signals arising from the voltage variation across the light level applied to each sensor and using specific algorithms to determine the flight heading. Computationally, the embedded micro-controller system reads and processes the data emanating from the sensors. They are ranked in decreasing order, electing the largest and the second largest values. Given the determination of these values, the equivalent quadrant is established and the sun position is estimated in real time.

Figure 11 illustrates the arrangement for operating the LDR opposite angular orientation of the aircraft heading. This Figure shows four different situations to identify the position of the sun for later estimation of the heading, which can be interpreted as follows:

A – Considers a cloudy atmospheric condition where there is no direct incidence of sunlight in quadrants. Another sensor is needed for estimating the heading, in this case, the COTS magnetic sensor.
B - Biggest solar incidence on quadrant Q1, heading with small angular variation in east.
C - Biggest solar incidence in quadrants Q1 and Q4, heading without angular variation and pointed to the north direction.
D - Biggest solar incidence in all quadrants indicates the sun in half, east-west cycle midday sun.

The initial setting of a bird's guidance sundial happens when the bird wakes up in the morning. It was shown that it is possible to vary according to the variation of the incidence angle of solar light on the bird [17].

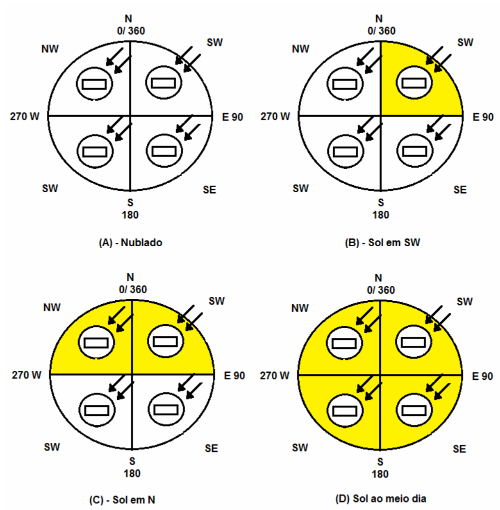

Fig. 11. Sun heading estimator mechanical setup and light incidence.

For the computational system development based on bio-inspired navigation system, the sun heading estimator has been installed on top of the Bio-UAV, with horizontal orientation, and pointed to the flight direction.

3 Experimental Results

The Bio-UAV prototype has been designed as being statically and dynamically stable in order to minimize the control load on the aircraft electromechanical equipment. Through a portable command station, it has been possible to control, monitor, and collect data of the UAV mission.

A specific flight profile has been defined to the controllers initial gain adjustment process and to acquire flight data for further analysis. The flight profile in the preliminary testes has included the following assumptions:

1. aircraft flying at 0 degrees (pitch, roll, and yaw), with constant speed, monitored in real time, the ground station receiving and storing the telemetry data from the aircraft in real time,
2. the Autopilot is turned on/off remotely by a human operator,
3. in a given time instant, the Autopilot is switched to on and a disturbance is applied, such as the deflection of the wing ailerons,
4. the previous sequence is repeated for all axes to allow for the control mesh adjustment.

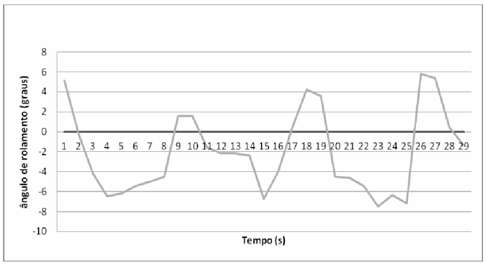

Fig. 12. Stabilizer response with preset control gains.

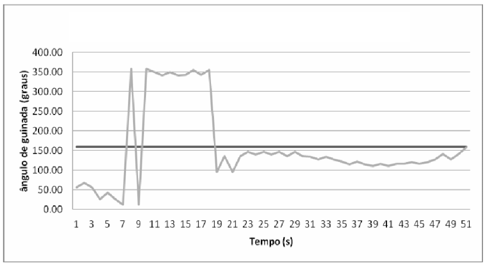

Fig. 13. Sun heading estimator applied at the yaw axis.

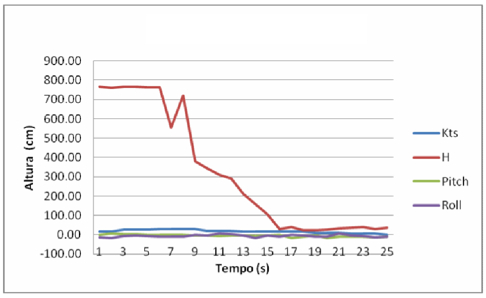

Fig. 14. Bio-inspired landing process.

Figure 12 shows the aircraft response in roll, considering the bio-inspired control method, with adjusted control gains through flight tests.

The same procedure employed for the rolling motion has been used to sun heading estimation, in this case affecting the yaw axis angle ψ. Figure 13 shows the yaw stabilization process, considering a preset heading. It is possible to observe that, for an initial heading of $\psi = 50$ degrees and for a desired final heading of $\psi = 150$ degrees, the aircraft performs successive turns until converging for the desired heading.

Figure 14 shows data obtained from the bio-inspired eco-localization process during the landing procedure. In this Figure, one can observe the status of the X, Y, and Z axes, as well the evolution of the aircraft speed and altitude, with the control gains already adjusted.

The conditions for the operation of the bio-inspired landing consider the roll angle constant, leveling the wing, while the pitch angle is varied according to the landing stage. The speed, represented in knots, suffers little variation because the system adopts a near stall speed. As a result, we have a successful landing. The aircraft altitude is measure in cm and is represented by H. Topographic variations of surface and eventual obstacles shall affect the sonar measurements and the calculations of the perfect landing ramp.

4 Conclusions

This work has shown that it is possible the creation of a low cost, small sized UAV system based on COTS equipment and bio-inspired features. A summary of the findings on the three bio-inspired features tested in this paper is presented here.

For a functional system, the bio-inspired features require a more enhanced development, obtained through more simulated and field tests. These features have been developed using the techniques of virtual reality, computer vision, and classical and non-classical control models to subsequently be encoded in computer language.

Line-of-Horizon Attitude - Through the use of computer vision techniques and considering assumptions suggested from zoological studies, it has been possible to establish a bio-inspired computational model capable of determining the UAV attitude, thus dispensing the use of equipment such as Inertial Measurement Units (IMU), routinely embedded in conventional systems. This result reduces the aircraft size and, above all, lower costs in the aircraft manufacturing system.

Eco-localization Landing Process - It has been seen that, through a model based on bats, with the use of a COTS sonar equipment, it is possible to change the sonar operating frequency for assistance in measuring the UAV landing ramp. For this purpose, besides employing the sonar in pre-determined ways, the functionality of the bio-inspired approach can be used for aircraft stabilization and attitude determination in the respective landing stages.

Sun Heading Estimator Navigation Process - The sun heading estimator, based on birds morphological and operational characteristics, can be used in the case of loss of the GPS signal (scenario) or even in regions where this device is for any reason un-available or in non-operational status. Considering that this system is based on the birds natural sun compass, it can be improved and applied for navigation refinement on the UAV aircraft heading, currently restricted to the determination of quadrants to help guiding the navigation.

It is worthy noting that the present development is still a concepts demonstrator for the three bio-inspired features investigated. For other applications and for commercial operations, further studies, process refinements and more ground and flight tests are required.

5 Acknowledgements

Partial support for this research stemmed from FAPESP grant # 11/50331-8 and from CNPq grant # 550572/2011-2. Additional support has been provided by CAPES, INCT, and the Brazilian Aeronautical Command (COMAER).

6 Contact Authors Email Addresses

Rodrigo Kuntz Rangel, DSc:
rodrigo.kuntz@brvant.com.br
Karl Heinz Kienitz, PhD: kienitz@ita.br
Mauricio Pazini Brandão, PhD: pazini@ita.br

References

[1] Fahlstrom, P. G. and Gleason, T. J., *Introduction to UAV Systems*, Maryland: UAV Systems Inc, 1998.
[2] Rangel, R. K., Kienitz, K. H., Brandão, M. P. *Development of a Multi-purpose portable electrical UAV system*. In: IEEE Aerospace Conference, 2011, Montana. Proc. Montana: IEEE, 2011.
[3] Rangel, R. K., Guimarães, L. N. F., and Brandão, M. P., *Development of an Unmanned Air Vehicle*, Paper 00026PE, SAE Brasil 2005 Proc., November 2005.
[4] Rangel, R. K., Kienitz, K. H., Brandão, M. P. *Development of a Complete UAV system using COTS equipment*, IEEE Aerospace Conference, Big Sky, MT, USA, 2009.
[5] Simons, M. *Model Aircraft Aerodynamics*, Philadelphia: Nexus Especial Interests, 1994.
[6] Dorf, R. C., Bishop R. H., *Modern Control Systems*, New Jersey: Prentice Hall, 2001.
[7] Tsui, J. *Fundamentals of Global Positioning System Receivers: A Software Approach*, John Wiley & Sons, EUA, 2000.
[8] Berger, A., *Embedded Systems Design: An Introduction to Processes, Tools, and Techniques*, CMP Books, EUA, 2001.
[9] Rangel, R. K., Guimarães, L. N. F., Brandão, M. P., Porto, F. M. *Development of an UAV Navigation System through a Synthetic Vision*, SAE Paper 2007-01-2561, SAE Brasil 2007 Proc., November 2007.
[10] Ogata, K. *Engenharia de controle moderno*. 4ª Ed. [S.l.]: Prentice-Hall, SP, Brasil. 2003.
[11] Luger, G. F. *Inteligência artificial*. 4ª Ed. Santana: Bookman, 2002.
[12] Negnevitsky, M. *Artificial intelligence*. Harlow: Pearson Education, 2002.
[13] Rangel, R. K. *Sistema VANT de monitoramento aéreo multiuso com funcionalidades bio-inspiradas*. 2012. 187 pp. Tese de Doutorado, Instituto Tecnológico de Aeronáutica, São José dos Campos.
[14] Rangel, R. K., Kienitz, K. H., Brandão, M. P. *Development of a Multipurpose Tactical Surveillance System using UAV's*. In: IEEE Aerospace Conference, 2014, Proc. Montana: IEEE, 2014.
[15] Mclean, D. *Automatic flight control systems*. New Jersey: Prentice-Hall International, 1990.
[16] Nascimento, C. Jr, Yoneyama, T. *Inteligência artificial em controle e automação*. 2ª Ed. São Paulo: Edgard Blucher, 2004.
[17] Pough, F. H., Janis, C. M., Heiser, J. B. *A vida dos vertebrados*. 3ª Ed. São Paulo: Atheneu, 2003.

Copyright Statement