Aeronautical and Avionics Design, Construction and Flight Test of the EFIGENIA EJ-1B Mozart Autonomous Unmanned Aerial Vehicle UAV

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I. Introduction

The EFIGENIA S/VTOL Unnamed Aerial Vehicle UAV project starts in December 1991. The project involved important engineering topics as in the Aeronautical areas as in the Electronics (hardware and software) areas, designing, building, and conducting the EFIGENIA UAV flight test.

The basic idea was to create an exceptional autonomous robotic flying machine that be capable of perform special and high risk tasks such as Rescue Works, Scientist Research support, in particular, collect environmental data to asses climatic change, atmospherical pollution analysis and geological survey. EFIGENIA also carry a small Forest surveillance and Fires prevention equipment, News transmission "in live" system, and a traffic monitoring report.

EFIGENIA S/VTOL unmanned aerial vehicle requirements was an enormous challenge, because of the variety objectives in this research project. This included topics such as:

1) The design and introduction of the S/VTOL Rotor and Tailless Forward Swept wing Concept unmanned aerial vehicle.

2) The design and development of an intelligent adaptive reconfigurable (on hardware) digital neural network guidance and navigation computer.

3) Design and development of multiprocessor DSP embedded Fuzzy Logic flight control system.

4) Air vehicle sensor instrumentation development (Real-time airborne control system, data acquisition, and video).

5) Tetelemetry and telecontrol system based on Reconfigurable Computation devices.

6) Neural networks fuzzy logic system integration for EFIGENIA intelligent avionics system architecture.

II. EFIGENIA UAV System Overview

The EFIGENIA UAV System configuration joins important topics of Aeronautics and Electronics technology. Every EFIGENIA UAV aircraft component was designed, builds and tested in the EFIGENIA Aerospace Robotics Research laboratory, including wings, fuselage, electronics equipment (hardware and software), propulsion units and station control.

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The EFIGENIA was designed and developed to validate and demonstrate the flying qualities and performance characteristics of a short or vertical take-off and landing (S/VTOL) unusual experimental unmanned aerial vehicle that gives to the aerial

Vehicle the vertical flight capability and low speed flight characteristics of a helicopter[1] and the horizontal cruise speed of a conventional aircraft[2, 3] (Figure 1).

Figure 1. EFIGENIA S/VTOL-UAV Airplane.

III. EFIGENIA UAV Airplane Design Philosophy

The EFIGENIA UAV is built of robust, lightweight, and high-strength materials. EFIGENIA aerospace design introduces an ***S/VTOL Rotor and Tailless Forward Swept Wing Concept*** with the purpose of allowing to the air vehicle an excellent aeromechanical behavior[4, 5].

The EFIGENIA is powered by two 2.0 HP engines located each one in the nose and tail fuselage respectively, and one more 2,25 HP engine inside the aerial vehicle body. In contrast, the tail engine has been adapted for conform a thrust vectoring unit to aimed high performance flight control system, maneuverability and agility at low speeds.

The air vehicle is capable of taking-off with a maximum weight of 8 Kg, endurance of 1,0 Hrs and reaching a maximum altitude of 7.000 Ft. The air vehicle control in Hover and transition modes is accomplished using a thrust vectoring unit which works in yaw and pitch axes. The control of the vehicle during forward flight is accomplished using split ailerons, small canard wing and flaps. Again, the thrust vectoring system remains active during forward flight mode; they contribute to the control power of the vehicle in this mode.

The EFIGENIA do not have vertical tail, hence, the control is provided by two split ailerons, canard mobile surface control and a thrust vectoring unit which works in yaw and pitch axes as shown in the Figure 2.

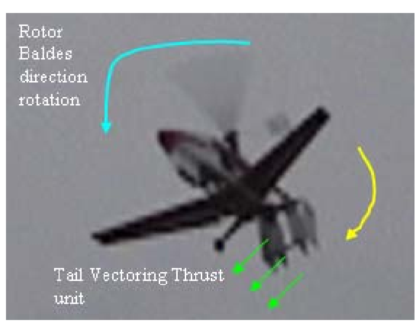

Figure 2. Tail vectoring thrust unit in action during flight test

A. System Operating Modes

The EFIGENIA S/VTOL-UAV can be operated in two modes. These include:

1) Fully Autonomous aerial vehicle in which the EFIGENIA has a complete autonomous operation.

Semi Autonomous in which augmented stability assisting to a pilot-operator in the control station.

B. Telemetry and Telecontrol Communication Systems

The communication systems are capable to transport data from the EFIGENIA UAV to the control station, and in the contrary way (control station to UAV). The Telecontrol commands are sent from the control station to the EFIGENIA as in remotely piloted mode as in autonomous flight mode. The Telemetry system includes two communication channels:

- The uplink channel which operates from the control station to the EFIGENIA UAV
- The Downlink channel which operates from the air vehicle to the control station

For this purpose I decided to develop an Adaptive Differential Pulse Code Modulation (ADPCM) Telemetry and Telecontrol System based on a reconfigurable hardware. This solution offer high performance for the telemetry and telecontrol digital processing data information. In this way, the data are encoded in each channel for the transmission over a UHF band data link, and decoded at the receiver to recover the individual data.

Additionally, the vision system consists of a CCD video camera onboard the EFIGENIA which uses an individual transmission channel for transfer the video signal between the vehicle and the control station, in Real-time (figure 3).

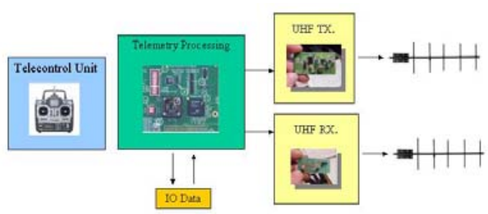

Figure 3. Telemetry and Telecontrol block diagram.

C. The Control Station

The flight operations of EFIGENIA UAV are specified by control station which because of its small physical dimensions could be resided onboard car, ship, airplane or ground. The control station continuously maintains communication with the airborne platform and payload.

This has been designed to operating under concept of "virtual Cockpit" which allows to the operator the possibility of feeling the realism of flight operations, flight conditions and its performance. The control station unit consists of an instruments screen panel, a control stick and a keyboard, which are used for selecting and monitoring the aerial vehicle operation. On the other hand, the mission control station unit generates all the information about the EFIGENIA UAV mission objective task (Figure 4 a, b).

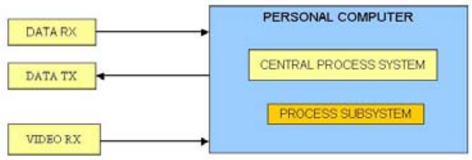

Figure 4 a. Station Control block diagram.

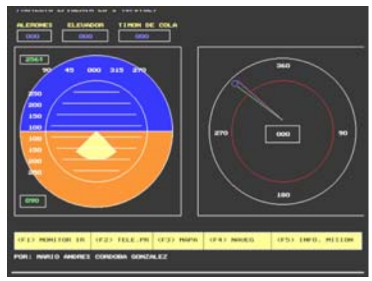

Figure 4 b. Flight instruments screen.

IV. Intelligent Autonomous Navigation, Guidance, and Flight Control System for the EFIGENIA S/VTOL-UAV.

The combination of neural network and fuzzy logic expert system make possible to create an effective method for implement the EFIGENIA autonomous navigation and flight control technique. In this way, the system allows a massive parallelism; learning ability, fault tolerance, etc., capabilities.

This system is divided in two important subsystems: The Adaptive Reconfigurable (on hardware) Digital Neural Network Guidance and Navigation Computer and the Fuzzy Logic flight control system computer.

A. Digital Neural Network Navigation Computer.

The EFIGENIA fuzzy logic flight control system drive the attitude of the vehicle. This means that the attitude information of the UAV vehicle must be measured every time. For this reason was designed a low-cost electronic Attitude and Heading Measurement System.

The electronic AHRS has been designed, constructed and tested based on three orthogonally mounted miniature MEMS gyros, three orthogonally mounted MEMS accelerometers and a three axis magnetometer along the body X, Y, Z axis.

The attitude of the EFIGENIA UAV was defined using three consecutive rotations[6, 7]. This angular rotation was referred as the Euler Angles (ψ, θ, ϕ) which determined the attitude of the UAV with respect to a local level reference frame[8].

The following rotations were applied:

- First, the body frame is rotated around the Z-axis by an angle ψ.
- Second, the body frame is rotated around the Y-axis by an angle θ.
- Finally, the body frame is rotated around the X-axis by an angle ϕ.

Thus, the Euler angles are given by[9]:

$$\dot{\phi} = p + \tan\theta\left(q.\sin\phi + r.\cos\phi\right) \quad (1)$$

$$\dot{\theta} = q.\cos\phi - r.\sin\phi \quad (2)$$

$$\dot{\psi} = \sec\theta.\left(q.\sin\phi + r.\cos\phi\right) \quad (3)$$

For the EFIGENIA UAV flight dynamics and mission profile the range of the Euler angles values (ψ, θ, ϕ) were limited with the purpose to avoid singularities from the trigonometric functions at certain angles.

This case was modeled in Simulink[10] as shown in figure 5.

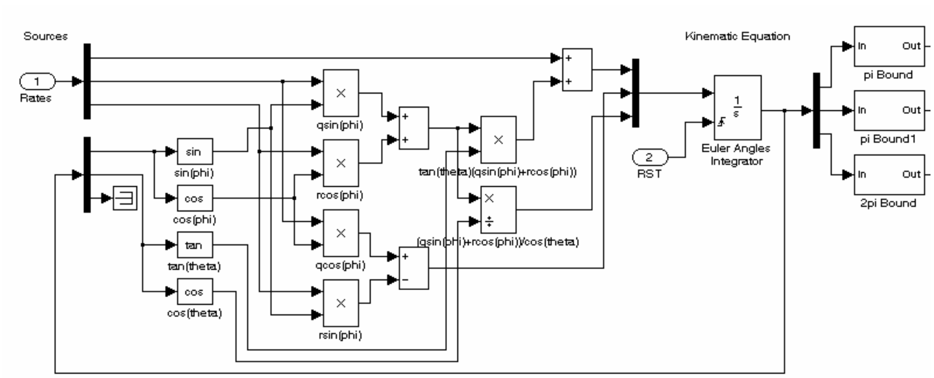

Figure 5. EFIGENIA UAV attitude representation and modeling using Euler angles.

B. Efigenia AHRS Electronics Hardware Design

The EFIGENIA UAV aircrafts perform its autonomous flight based on an embedded Fuzzy Logic Fight Control System architecture. The EFIGENIA fuzzy logic flight control system drive the attitude of the vehicle, this means that the attitude information of the UAV vehicle must be measured every time. For this reason was designed a low-cost electronic Intelligent Attitude and Heading Measurement System I-AHRS, Figure 6.

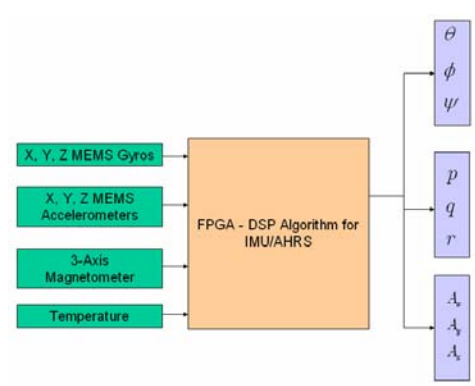

Figure 6. EFIGENIA designed I-AHRS block diagram

The electronic I-AHRS is composed by three important parts: the sensor board, the processing main board and the neural network attitude estimation scheme.

The sensor board has been designed, tested and constructed based on three orthogonally mounted miniature MEMS gyros, three orthogonally mounted MEMS accelerometers and a three axis magnetometer along the body X, Y, Z axis.

The processing main board is based on a reconfigurable programmable logic device FPGA which run the digital neural network and a dspic30F4013 digital signal processor as a system coprocessor.

The intelligent attitude heading and reference system I-AHRS electronic hardware design has been based on MEMS gyros and accelerometers and magneto-resistive transducers.

The MEMS transducer output an electrical signal (voltage) proportional to the physical variable sensed in the UAV, in this case, angular velocity and acceleration.

Using the MEMS technology on those sensors, the hardware cost and the physical size of the circuits are reduced representing and advantage for the use at the avionics section of the EFIGENIA UAV. The I-AHRS is composed by three ADXRS150 gyros mounted orthogonally for measure the angular velocities { p, q, r }, and three ADXL203 accelerometer transducers with it's respectively axes { A_X, A_Y, A_Z } aligned with the EFIGENIA UAV aircraft axes. Finally the system add a 3-axis magneto-resistive transducer { H_X, H_Y, H_Z } for complete the data set information of the unit.

The accelerometers are used in the electronic I-AHRS to measure tilt angles with respect to gravity, and as navigation system data inputs.

The transducer used for acceleration measurement is a $\pm 1.7g$ surface micromachined device. This offer low noise, wide dynamic range, reduced power consumption and improved $zero - g$ bias drift.

Each transducer is a two sensitive axes, orthogonal (90°) to each other. The device has their sensitive axes in the same plane as the silicon chip, Figure 7.

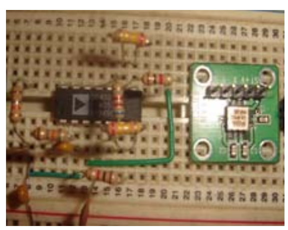

Figure 7. I-AHRS accelerometer electronic circuit

Typical noise density level intrinsic to the device is $110\left[\frac{\mu g}{\sqrt{Hz}}\right]$ RMS, and the device typical scale factor is $1000\left[{}^{mv}\!/_{g}\right]$ with a sensitivity drift due to temperature of $\pm 0.3\%$.

Due to the nature of accelerometer transducer device construction, the output voltage (V_{out}) is a function of both the acceleration input (a) and the power supply voltage (V_s) as shows in Figure 8.

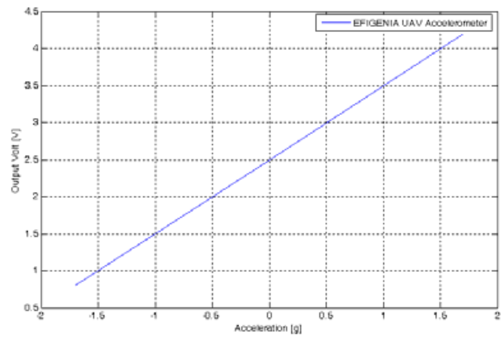

Figure 8. AHRS accelerometer transfer function

These accelerometers, as inclinometer, measure an angle relative to the force of gravity, and have a too low band-width (slow response) to be able to control the attitude of the EFIGENIA UAV.

Table II list the accelerometer transducer performance used in the I-AHRS circuit design.

TABLE II
ACCELEROMETER TRANSDUCER SPECIFICATIONS

Parameter	X-Y-AXIS	Z-AXIS
Range	$\pm 1.7[g]$	$\pm 1.7[g]$
Sensitivity	$1000\left[{}^{mV}\!/\!_{g}\right]$	$1000\left[{}^{mV}\!/\!_{g}\right]$
Frequency Response	5.5 KHz	5.5 KHz
Supply Voltage	5 V	5 V
Operating Temperature	-40 to 85 deg	-40 to 85 deg
Noise Performance	$110\left[{}^{ug}\!/\!_{\sqrt{Hz}}\right]$	$110\left[{}^{ug}\!/\!_{\sqrt{Hz}}\right]$
Non-Linearity	0.5% of FS	0.5% of FS
Alignment Error	$\pm 1\circ$	$\pm 1\circ$

The I-AHRS designed use angular rate sensors to measure the rate of rotation about each axis. The outputs of each gyro are the analog voltage in response to its angular rate physical movement.

The three gyros are mounted in orthogonal way that allow to measure the angular velocities p, q, r, around the accelerometer axes system, Figure 9.

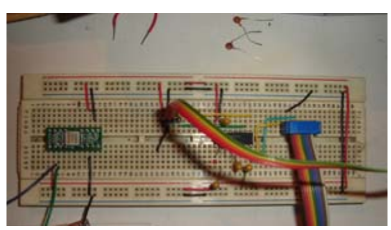

Figure 9. I-AHRS angular rate sensor electronic circuit

Three angular rate transducer units are required to sense all three UAV aircraft axis (Pitch, Roll, Yaw), and each reports it axis rotational sensing in the form of difference analog outputs. The angular rate offering by these gyros are acceptable in terms of band-width and are used to find the attitude angle by integration, over the time, of the sensor output data on each axis.

At this point, the big problem is that due to the numerical integration process the measurements errors are accumulated causing drift on the angular measurement, and then is necessary to apply a correction procedure.

The system has one angular rate sensor per axis, giving an analog voltage output that is proportional to the rotational turn-rate about each axis.

Figure 10 represents the transfer function of the angular rate transducer.

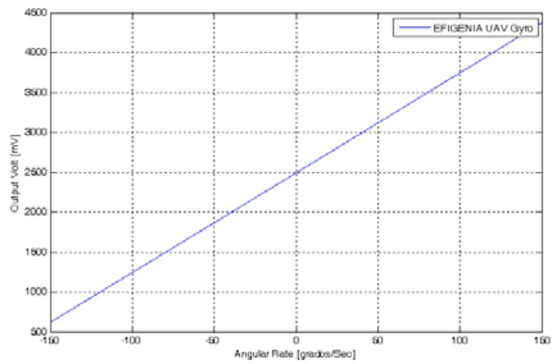

Figure 10. I-AHRS angular rate transfer function

The detailed specification for the angular rate transducers used in the EFIGENIA intelligent attitude and heading reference system is listed below in the Table III.

The rate gyro data is sampled at 100 Hz, given a good response about the EFIGENIA UAV autonomous aircraft attitude over short periods of time.

These sensors provide an output proportional to the rotation rate contaminated by noise and with the so called drift effect.

For the short periods of time the drift can be approximated by a constant bias, and the orientation can be evaluated with a single integration of the angular rate signal output.

TABLE III
ANGULAR RATE TRANSDUCER ESPECIFICATIONS

Parameter	X-Y-AXIS	Z-AXIS
Range	$\pm150\left[{}^{dec}\!/_{\sec}\right]$	$\pm150\left[{}^{dec}\!/_{\sec}\right]$
Sensitivity	$12.5\left[{}^{mV}\!/_{{}^{\deg}\!/_{\sec}}\right]$	$12.5\left[{}^{mV}\!/_{{}^{\deg}\!/_{\sec}}\right]$
Frequency Response	40 Hz	40 Hz
Supply Voltage	5 V	5 V
Non-Linearity	0.1% of FS	0.1% of FS
Axis-Misalignment	$\pm1\circ$	$\pm1\circ$
Noise	0.05 deg/s/ $\sqrt{Hz}$	0.05 deg/s/ $\sqrt{Hz}$

The transfer equation returns the rotation angle with two added terms. A random walk due to the noise and other term that grows with time proportional to the gyro bias.

The maximum random walk error is proportional to the noise standard deviation and the square root of time. This error has to be considered in case where this value is comparable with the expected drift of the gyro.

Another aspect that needs to be considered is the resolution of the analog to digital converter A/D used. The gyro output data is connected to a 12-bit A/D, returning a 0 to 4096 numerical value that corresponds to the ratio of the input voltage (0 to 5V).

The frequency response is critical to the proper system operation. In this way, it has been decided to implement a 5th order low-pass filter to filter the high frequency noise on the gyro output signal.

As result of the integration procedure, the value of the angular rate sensor in steady position suffer of an offset drift action respect of its initial steady position value because of the integration over long periods of time.

As a one solution for this problem has been developed a Neural Network scheme for estimate the EFIGENIA UAV attitude orientation in which are fused the 3-axes gyros, accelerometers and magnetometer sensors data.

The magnetometer sensor is used to provide heading information. In this case, was used a 3-axis solid state magnetic transducer sensitive to the earth's magnetic field, figure 13.

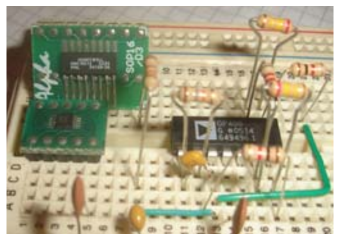

Figure 13. I-AHRS magnetometer circuit

A digital signal processor DSP (dspic30F3013) transforms the 3-axis X, Y, Z measurements to a coordinate system calculating the components as follows:

$$H = \sqrt{X_H^2 + Y_H^2} \qquad (4)$$

And then:

$$\psi = \arctan\left(\frac{Y_H}{X_H}\right) \qquad (5)$$

Table IV shows the Magneto-resistive transducer specifications for the EFIGENIA UAV I-AHRS SYSTEM.

TABLE IV
MAGNETO-RESISTIVE TRANSDUCER ESPECIFICATIONS

Parameter	X-Y-AXIS	Z-AXIS
Sensitivity	$1.0\left[{}^{mV}\!/_{V}\!/_{gauss}\right]$	$1.0\left[{}^{mV}\!/_{V}\!/_{gauss}\right]$
Frequency Response	5MHz	5MHz
Noise Density	$50\left[{}^{nV}\!/_{\sqrt{Hz}}\right]$	$50\left[{}^{nV}\!/_{\sqrt{Hz}}\right]$

The measured outputs of the magnetic transducer, X and Y, are plotted showing a circle as illustrated in Figure 14.

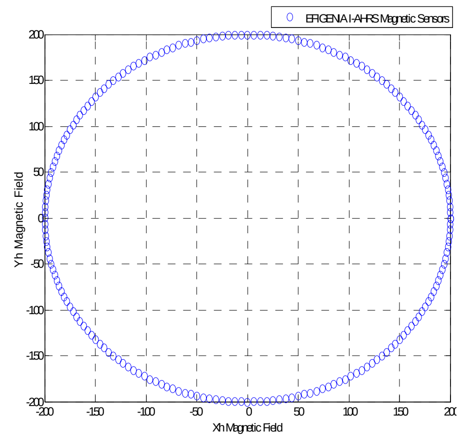

Figure 14. I-AHRS Magnetic transducer outputs X vs Y

C. Efigenia Air Data System Design

The air data system designed are composed by a temperature, airspeed, altitude, and rate of climb instruments indicators. EFIGENIA´s air data system has pressure probes for total pressure, static pressure, temperature and air flow direction. This probes are feeds to differential pressure transducer , absolute pressure transducer, temperature sensor, and air data vane for measure characteristics of the air flow surrounding the unmanned air vehicle, figure 21.

Figure Pitot Static Probe System

The air speed indicator is based on a piezoresistive transducer which is basically a differential pressure gauge, The airspeed instrument's heart is a dual ported piezoresistive monolithic silicon pressure transducer with temperature compensation, figure……

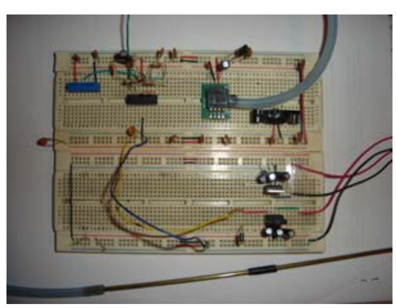

Figure 22. Airspeed indicator circuit

Pressure measurements for airspeed are shown in figure 24.

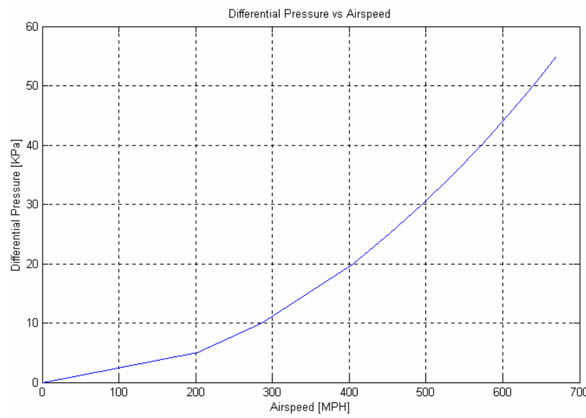

Figure 24. Pressure measurements for airspeed

The altimeter system is based on a 115 KPa temperature compensated absolute ported barometric pressure transducer, that measures this physical variable and process this signal value for converting to altitude value on the instrument, figure…

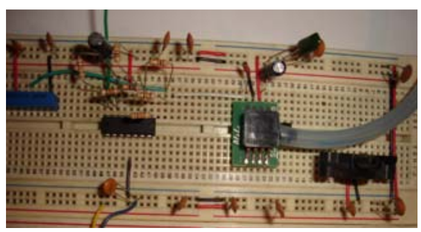

Figure 28. Altimeter electronic circuit

This altimeter indicator instrument was calibrated using the standard atmosphere and altitude indicated by the instrument is the *pressure altitude*. The range of altitude for the EFIGENIA EJ-1B UAV instrument is form 0 to 10.000 Feets.

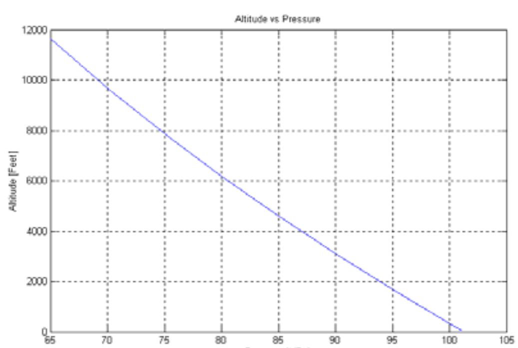

Figure 31. Altitude vs Pressure

The pitot and static sensor were calibrated in the wind tunnel as you can see in the figure 34.

Figure 34. Air data system calibration at the USB University wind tunnel laboratory

D. Digital Neural Network Attitude Estimation Filter design

Artificial neural networks have been used in a wide variety of robotics applications. The idea in the inertial sensor data fusion filter is to combine the outputs of the accelerometer, angular rate and magnetometer sensors to obtain a good estimate of the orientation attitude, calculating an error data between the estimated angles and the physical system angles[11], figure 6.

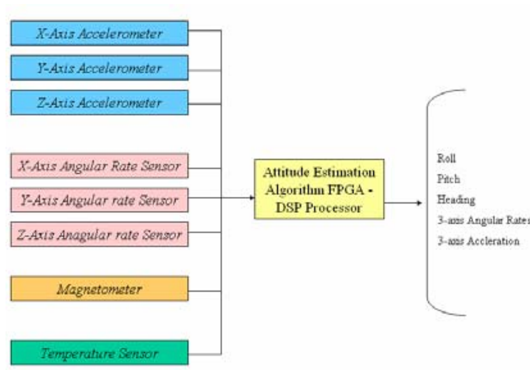

Figure 6. Attitude estimation block diagram

The idea in the EFIGENIA digital neural network AHRS computer was to make an ideal technique for improve the aerial vehicle attitude calculation and estimation process.

This AHRS computer is designed based on multiple parallel interconnected digital neural network chips architecture system that was designed specially for the EFIGENIA air vehicle.

During the flight, the system combines the data information from multiple sensors such as accelerometers, angular rate gyros, and magnetic sensors. The objective of this process is to provide high accuracy and low cost reliable system solution that ensures to the EFIGENIA enhanced orientation accuracy and minimized common errors from the system.

For this purpose, was used a multilayer digital neural network as on-line learning estimator[12] because of its high performance in multivariable and non-linear systems. In this way, the first step in the development of the AHRS computer was the design and development of a **FPGA *digital neural network chip.***

This chip is based on reconfigurable FPGA logic device, which contains important amount internal neurons (process elements). Each neuron processes a 16 bits inputs, and weights. All weights are stored in an external chip memory.

Due to the parallel distributed processing properties of the artificial neural networks, the chip developed for this attitude computer allows that multiple chips can be interconnected to expand the network, taking advantage on important system characteristics such as high digital processing speed, and fault-tolerance.

All sensors, gyros, accelerometers and magnetometers are mounted in a strap-down way. This gives more flexibility and reliability to the design, in other words; this means software mathematical transforms computation rather mechanical operations.

The EFIGENIA UAV AHRS digital neural network computer employ these, inertial sensors, and magnetic sensors as inputs to the system which allow to compute the most effective attitude operation and obtain high accuracy outputs enhancing the AHRS performance.

E. AHRS Neural Network Computer Architecture design

The implementation of artificial neural networks is mostly done on a conventional processor computer board, in which this job consuming a long run time periods.

As this system integrate data stream from the all different sensors to build a consistent model that represent the features of the UAV aircraft attitude sensed and to provide continuous accuracy stabilization, then was developed a solution for the run time and speed processing, implementing the neural network on a parallel reconfigurable computer based on Cyclone II Field Programmable Gate Arrays (FPGA) combined with a dsPIC30F4013 Digital Signal Processors (DSP), because of the fast prototyping, reusability and high speed run-time data processing.

Field Programmable Gate Arrays FPGA is the core of AHRS computer of the EFIGENIA EJ-1B Mozart S/VTOL Unmanned Aircraft. In the first layer (input layer) was implemented 24 artificial neurons, the second layer or so called hidden layer are composed by 24 artificial neurons, and the output layer (3rd neural network layer). The AHRS digital neural network computer employs the inertial sensors, and magnetic sensors as inputs to the neural network input layer. Then the reconfigurable neuro-computer starts de processing. The back-propagation neural network requires training information for supply the system with some sort of "experience". In this way, the network must be trained using a learning rule: This process consist in providing external patterns which are compared with the network outputs through the training phases. As this system is a multiple layers of neurons with non-linear transfer functions, then the network can develop a non-linear/linear relationship between input and output data vectors. This learning rule is used to estimate the neural network weights values, minimizing the sum squared error (delta) and adjusting continually the value of the weights.

F. Guidance System Computer Architecture Design

The EFIGENIA EJ-1B Mozart UAV guidance system steering toward a destination waypoint position from the actual UAV position, providing commands for track a predetermined flight path plan, including course, altitude, and airspeed. In this system is possible to loading up to 20 waypoints in which each of this is associated with a Longitude, Latitude and Altitude data information. Upon the EFIGENIA UAV arrival at the waypoint the air vehicle can proceeding with the next waypoint programmed in the list, or can enter in a holding pattern.

The guidance algorithm strategy is based on track-bearing error to reach waypoints. This guidance block conform the outer loop of the EFIGENIA UAV intelligent system in which steering solution are calculated and transmitted to the Fuzzy Logic Flight Control System multiprocessor computer which executes the steering commands using the aerodynamics control surfaces, and the 2 engine power-plant control units, figure 7.

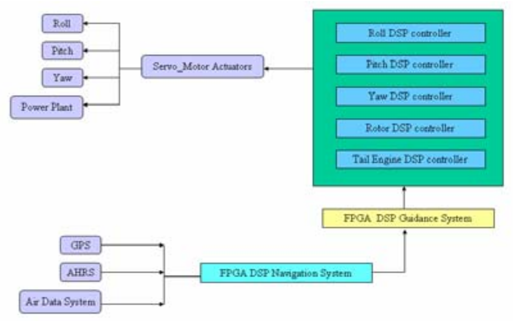

Figure 7. Autopilot block diagram

Upon arrival at each waypoint, a new waypoint data is to bring, thus selecting a new desired track value, or loading a holding pattern. This guidance system scheme was modeled as shown in figure 8.

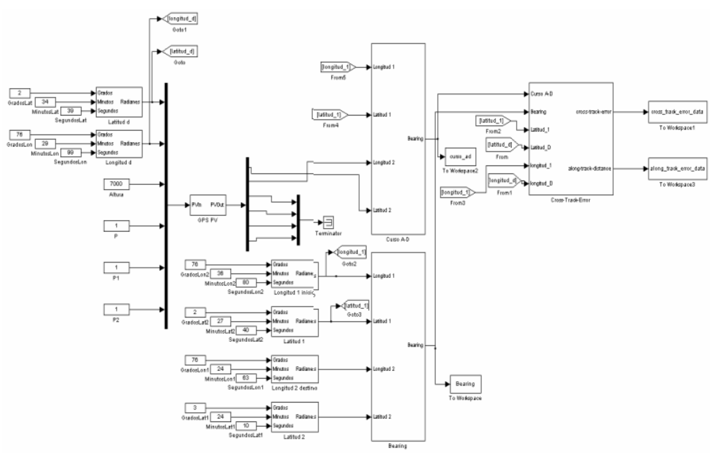

Figure 8. Guidance calculation and modeling

Each waypoint is defined by its associated 3D coordinate values: Latitude, Longitude, and Altitude. Then, for each waypoint a surrounding zone is defined as ***"arrival waypoint zone"*** in which the UAV aircraft is assumed to have passed over the target waypoint, and immediately activates the next waypoint in the list, figure 9.

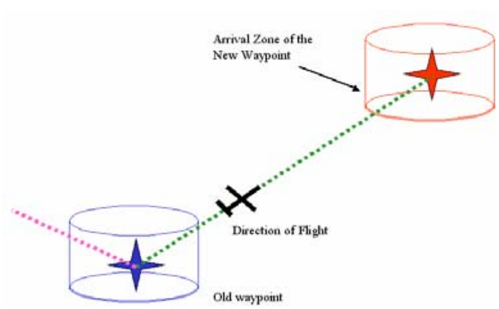

Figure 9. 3D Coordinates arrival waypoint zone

In the case of non-exist additional target waypoint in the list (final trajectory) then the UAV aircraft will perform a holding pattern over this last 3D position maintaining the altitude and speed.

G. Fuzzy Logic Embedded Flight Control System

The EFIGENIA UAV embedded digital flight control system architecture is implemented using fly-by-wire techniques[13]. All control laws computations are performed by a multiprocessor system computer based on nine DSP microcontrollers which run a Fuzzy Logic flight-control loops software at 90 million instruction per second (MIPS). For facilitate the flight control tasks, the EFIGENIA has a wide amount of sensors placed over the body and wings, which allow collecting data for its proper functioning.

Hence, the system uses all this data information for the digital fuzzy logic control processing and compute commands to the servo actuators that provide the desired surface deflection and/or engines parameters control obtaining the UAV aerial vehicle response.

Each DSP microcontroller perform its own independently real-time task aimed a high process speed, and optimizing the fuzzy logic flight control loop algorithm performance, figure 10.

The modular architecture and construction of the EFIGENIA navigation, guidance and fuzzy flight control system provides a number of benefits, including accommodation for future growth or configuration.

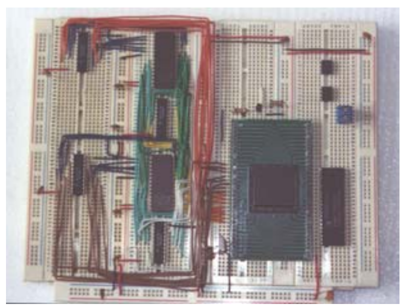

Figure 10. Flight controller (dspic30F4013) DSP circuit diagram

The system was divided into five principal and parallel fuzzy controller blocks which are divided again into more subsystems (fuzzy logic inner loops and outer loops). Figure…..

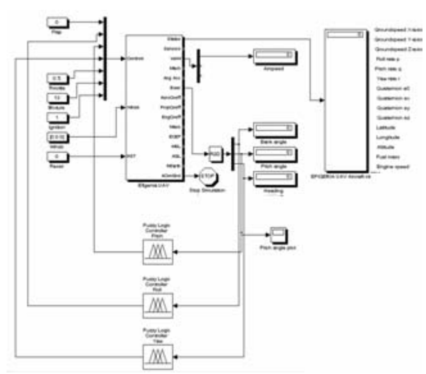

Figure ... Fuzzy Logic controller autopilot simulation

A Mamdani Fuzzy Logic controller is a Multi Input/ Multi output system that in the absence of an exact physical plant model, uses the knowledge of the operation control of a given system[14], in this case the EFIGENIA EJ-1B Mozart S/VTOL UAV unmanned aircraft, codifying this in terms of ***IF-THEN*** rules.
The figure 11 shows the block diagram in which is possible to identify the fuzzy logic flight control autopilot parameters.

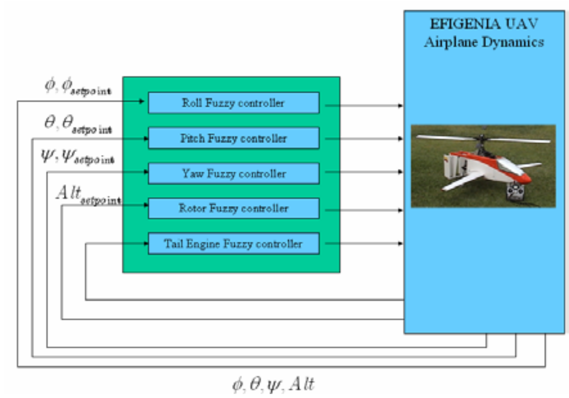

Figure 11. Block diagram for the fuzzy logic controller autopilot

The procedure was to apply commands for controlling the attitude angles ϕ, θ, ψ and the desired altitude.

The main idea in the fuzzy logic controller autopilot is to compute the desired attitude angles and the desired flight altitude and send the computed data to the inner-loop fuzzy controller blocks in which the outputs are the values for the EFIGENIA UAV actuators such as the cyclic, collective, flaperons, engine power and tail vectoring thrust vanes angle.

V. Fuzzy Logic Flight Control Implementation

H. Longitudinal Control loop

Figure 10 shows the lateral view of EFIGENIA S/VTOL UAV aircraft in a hover flight and the vector forces acting on it. The green arrow that going straight down represents the UAV weight vector due to gravity force.

The yellow arrow is the Lift vector which is generated by the rotor blades. In a hover flight, the lift force equals the weight, and the EFIGENIA S/VTOL UAV aircraft doesn’t descent or climb.

Figure 10. Lateral view of the EFIGENIA UAV in hover flight mode

Therefore, one of the fuzzy logic control computers command the amount of Lift in a hover flight mode to keep the UAV in a stationary vertical attitude, controlling the rotor engine speed and power and the collective of the rotor blades.

In the EFIGENIA UAV the main rotor blades rotation is performed to the right direction (clockwise), and the problem at this point is that all the forces acting on the UAV S/VTOL aircraft must cancel out to keep the EFIGENIA stationary.

Newton third law of motion states that for every applied force, there is an equal and opposite reaction force. This means that as the main rotor turns to the right direction the fuselage tries to turn to the opposite direction (counterclockwise).

For this reason, the purpose of the vectoring thrust propulsion engine unit on the fuselage tail is to compensate the torque reaction controlling the UAV nose pointing direction, Figure 11.

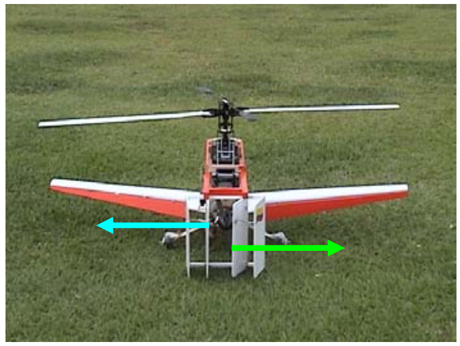

Figure 11. Tail vectoring thrust range of movement

Hence, if the thrust vector power of air in the tail is increased and pointed to the left, the UAV will rotate around of its center of gravity causing the nose to pointing to the right, and in the same manner, if the thrust vector power of air in the tail is decreased and/or pointed to the right, the UAV nose will go to the left, Figure 12.

Figure 12. Tail vectoring thrust unit in action during flight test

To allow to this UAV aircraft climb, one of the flight DSP controller increase the lift so that it's greater that the vehicle weight, commanding the rate of ascent parameter. This procedure can be performed by increasing the rotor speed and/or by increasing the pitch of the rotor blade.

In the fuzzy logic longitudinal control loop, the controller was divided in three fuzzy block subsystems in which each block depend of the sensor data associated to the axis information or the information preprocessed in the previous subsystem.

I. Lateral Control loop

The first idea is that, based on the helicopter theory, the Lift vector force of the rear rotor disk section is greater than the front section, causing that the tail rise and nose descending movement.

When The EFIGENIA has performing a transition to forward flight, the vertical amount of Lift force must continue to equal the weight vector to keep it at constant altitude. Split the Lift vector, into vertical and horizontal components, the horizontal component of Lift vector determines the amount of force to drive the aircraft in the forward direction.

At the same time, one DSP controller processor calculates the airspeed and when the S/VTOL UAV aircraft has achieved the calculated fixed forward swept wing speed for lift generation, the tail engine contributes with a portion of thrust.
The pitch control DSP processor governing the swashplate rotation, causing changes in the rotor Lift characteristics depending the commands send it. This movement of the swashplate controls the nose up or dawn attitude

In a similar way, a differential Lift vectors from one side of the rotor disk to the other, and making use of the differential flaperons placed on the fixed forward swept wing, the EFIGENIA UAV is enable to bank either to the right or to the left.

In this case, the swashplate receive right and/or left commands from the processor control, causing that the UAV move in the respectively direction. In the fuzzy logic roll control were use two internal fuzzy control loops, offering the following architecture.

J. Directional Control loop

The movement of the UAV nose body fuselage right and left is controlled by the tail vectoring thrust engine unit and is called yaw movement.

The vectoring thrust engine unit system counteracts the torque of the UAV rotor blades and makes changes in the thrust output level causing that the system can also change the nose pointing direction.

In forward Flight mode, the rotor system produce an increased Lift force due to the high air-flow velocity and mass of air per unit of time in the rotor disk, and the fixed forward swept wing contribute with additional Lift to the vehicle.

For the directional fuzzy logic control loop, was used the subsystem blocks strategy, offering the following architecture.

VI. EFIGENIA UAV FLIGHT TEST PROGRAM

The idea in this phase is to measure and validate the performance of the EFIGENIA UAV aircraft system based on a series of ground and flight experimental tests.

A. Ground Test

The ground test consists of the following steps:

1) UAV Aircraft structural verification test.
2) Rotor system test.
3) Propulsion system test.
4) Landing gear test.
5) Power consumption test.
6) Telecontrol system test
7) Telemetry system test.
8) Sensors and Instrumentation test.
9) Computers operation test.
10) Servo-actuators test.
11) EMI test.
12) Vibration test.

B. Flight Test Results

Flight test data information is recorded by the avionics flight data recorder memory computer. This information is stored on a memory system structured.

C. First Flight Test

The first flight test was developed all in manual / semi- autonomous mode, controlled by the flight test pilot. This first experimental flight test offered important information about the EFIGENAI UAV aircraft performance dynamics operation, stability and controllability, figure 12.

Figure 12. First Flight Test (Manual / Semi-Autonomous Mode)

D. Autonomous Flight Mode Flight Test

This flight attempt was be at only several meters of altitude in autonomous flight mode, figure 13.

Figure 13. Shows the EFIGENIA UAV during autonomous flight.

The next step was started from the hover position and next performs a transition flight to cruise forward flight flying a circuit segment as shown in figure 14.

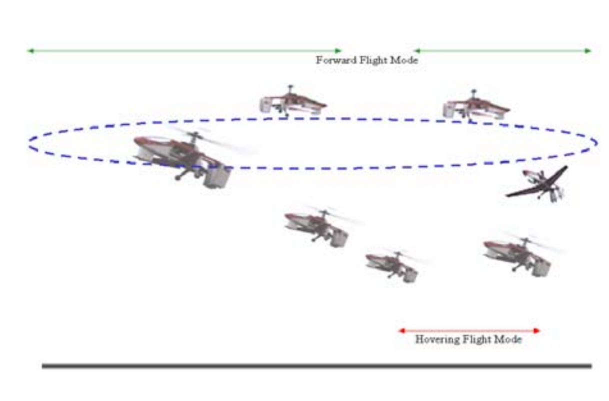

Figure 14. Efigenia autonomous transition and forward flight

VII. Conclusion

This paper has presented the EFIGENIA EJ-1 short or vertical take-off and landing (S/VTOL) Autonomous Intelligent Unmanned Aerial Vehicle development and implementation in which the use of new technologies as in the Aerospace as in the Electronics sciences offer a high performance solution in the unmanned systems scientific research field.

At the same time, EFIGENIA S/VTOL-UAV is an attempt to contribute with the enhancement of human kind quality life level.

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