THE EFIGENIA EJ-1B MOZART S/VTOL Aerial Robotics Autonomous UAV Autocontrolled with an Artificial Intelligent Embedded Guidance, Navigation and Flight Control System

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Abstract—**This paper describes the EFIGENIA EJ-1 Short or Vertical take-off and Landing (S/VTOL) autonomous intelligent Unmanned Aerial Vehicle (UAV). The EFIGENIA EJ-1 is an advanced aerodynamics design vehicle and avionics autopilot system design in which a digital neural network combined with a fuzzy logic system performs the best flight guidance, navigation and flight control condition operation.**

I. INTRODUCTION

THIS he 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 SVTOL AERONAUTICAL DESIGN

A. 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.

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).

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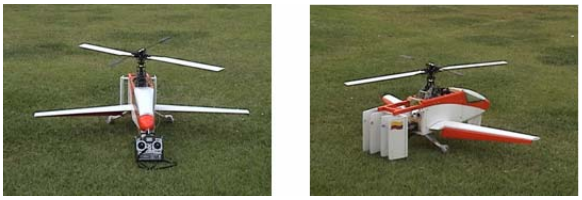

Figure 1. EFIGENIA S/VTOL-UAV Airplane.

B. Efigenia Aerial Robot 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.

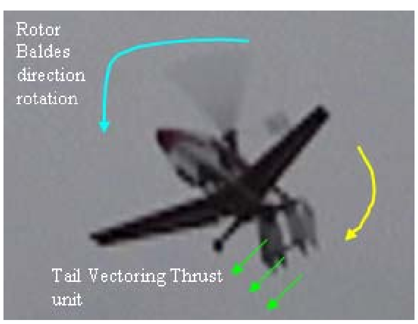

Figure 2. Tail vectoring thrust unit in action during flight test

C. System operating Modes

The EFIGENIA S/VTOL-UAV can be operated in two modes. These include: Fully Autonomous aerial vehicle in which the EFIGENIA has a complete autonomous operation; and Semi Autonomous in which augmented stability assisting to a pilot-operator in the control station.

D. Telemetry System

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:

1) The uplink channel which operates from the control station to the EFIGENIA UAV

2) 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).

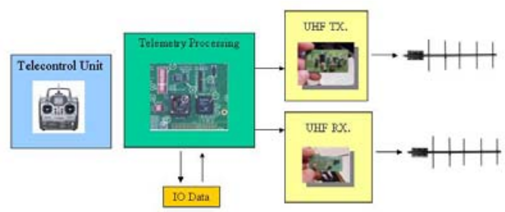

Figure 3. Telemetry and Telecontrol block diagram.

E. Control Satiation

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).

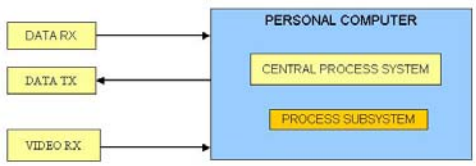

Figure 4 a. Station Control block diagram.

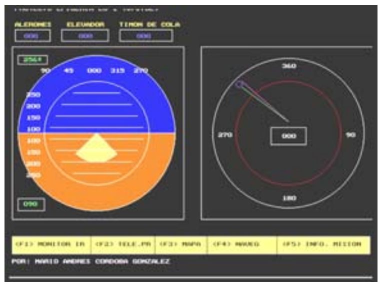

Figure 4 b. Flight instruments screen.

III. INTELLIGENT GUIDANCE, NAVIGATION 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. Adaptive Reconfigurable (on hardware) Digital Neural Network Guidance and 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, 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 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:

1) First, the body frame is rotated around the Z-axis by an angle ψ .
2) Second, the body frame is rotated around the Y-axis by an angle θ .
3) 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.

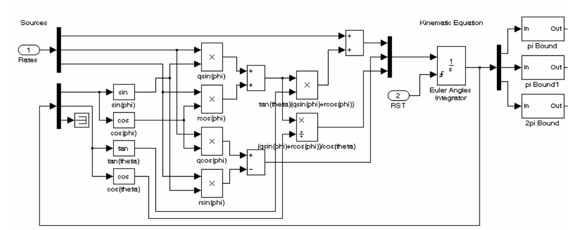

Figure 5. EFIGENIA UAV attitude representation and modeling using Euler angles.

B. 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.

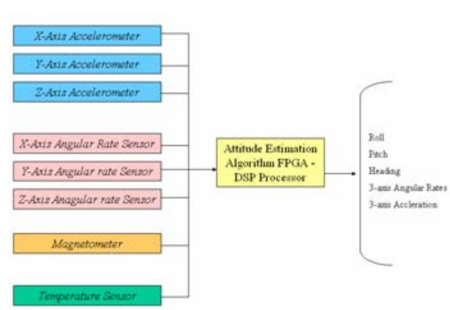

Figure 6. Attitude estimation block diagram.

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.

C. 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 Field Programmable Gate Arrays (FPGA) combined with a 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.

D. 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.

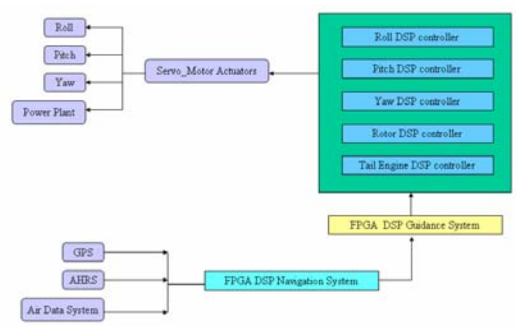

Figure 7. Autopilot block diagram

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.

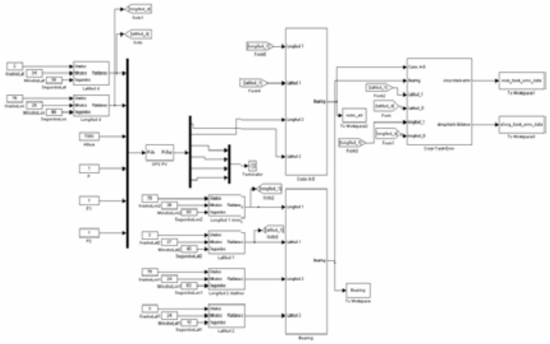

Figure 8. Guidance calculation and modeling

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.

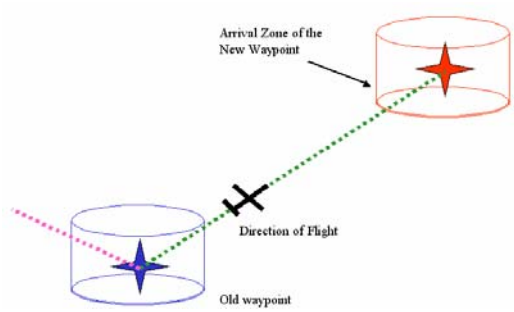

Figure 9. 3D Coordinates arrival waypoint zone

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.

IV.   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.

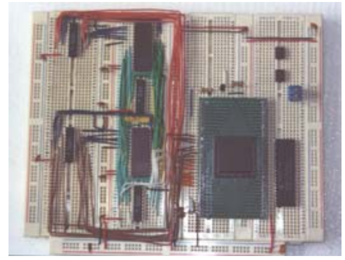

Figure 10. Flight controller (dspic30F4013) DSP circuit diagram

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).

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.

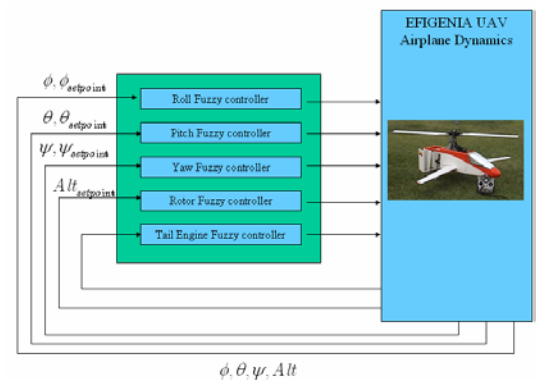

Figure 11. Block diagram for the fuzzy logic controller autopilot

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.   EFGENIA UAV FLIGHT TEST RESULTS

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. *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)

C. *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.

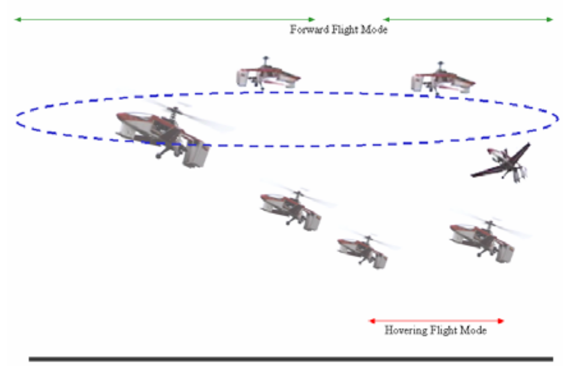

Figure 14. Efigenia autonomous transition and forward flight

Figure 15 shows the behavior of the system during a test.

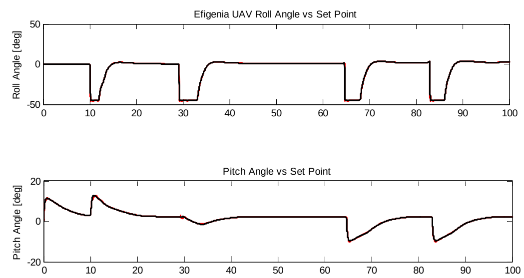

Figure 15. Longitudinal and Lateral Fuzzy Logic controller test.

VI. 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.

VII. Acknowledgments

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