CP. 594

AUTOPILOT SYNTHESIS FOR UNMANNED TACTICAL AIR VEHICLES (UTAV)

P. Faggion
L. Zolla

ALENIA Difesa
Avionic Systems and Equipment Division
Strada Aeroporto, 10072 San Maurizio C.se (Torino), Italy.
Tel. (39)11-9967 817; Fax (39)11-9967 694

SUMMARY

This paper presents an overview on the AutoPilot design philosophy for a medium class, jet powered Unmanned Tactical Air Vehicle (U.T.A.V.) and the development of its Rig + Advanced Integrated Data Acquisition & Simulation System (Rig + AIDASS). After a short description of the Mirach 150 U.T.A.V. system, the synthesis methodology of the primary control laws for the steering and navigational modes are presented (Autopilot and Flight Management System). The process aims at verifying accordance between requirements and performances of the global system (Autopilot+Airframe). The performances of the system are shown: dynamic responses in front of altitude, groundspeed and heading demands and their maintenance in presence of atmospheric turbulence (MIL-F-8785/C). The study is developed in FORTRAN 77 language.

LIST OF SYMBOLS AND ABBREVIATIONS

6DOF	6 Degree Of Freedom
ADC	Air Data Computer
AHRS	Attitude and Heading Reference System
AIDASS	Advanced Integrated Data Acquisition & Simulation System
AP	Autopilot
δ_a	Aileron deflection angle
δ_e	Elevator deflection angle
FMS	Flight Management System
GPS	Global Positioning System
IAS	Indicated Air Speed
p	Roll rate
q	Pitch rate
SAS	Stability Augmentation System
TAS	True Air Speed

KEYWORDS

AutoPilot, PI Control Laws, Self Tuning, Unmanned Tactical Air Vehicles, Simulation.

1. INTRODUCTION

Herein are presented the main steps of the design methodology employed for the Mirach 150 FMS/AP project development. MIRACH 150 is an ALENIA's carrying out for the Italian Army: a high speed Unmanned Tactical Air Vehicle derivative of the MIRACH 100 target drones family.
The procedure herein described is completely computer-aided to simulate the behaviour and performances theoretically achieved at the end of the design phase.
First of all, a mathematical model of the airframe+sensors has been implemented on a VAX computer, based upon airframe and equipment suppliers' database; then, the classical Equations of motion have been implemented to build a real 6 Degree Of Freedom (6DOF) Model.
The third step consisted in the linearisation of the motion equations to extract the transfer functions needed to outline the autopilot loops: the inner loop Stability Augmentation System (SAS), the attitude autopilot, and then the outer loop: the steering and navigational autopilot.
These control laws have been subsequently implemented on the 6DOF model to evaluate their response in a test and trial sharpening process.
In order to evaluate the performances of the whole UTAV+FMS/AP system, an Avionic Integration System called Rig has been developed. It is made up of a phisical bench, on which lies the UTAV and its avionic equipment and an AIDASS which acquires all the data to be monitorized, and simulates the motion and external environment.

2. MIRACH 150 UTAV SYSTEM

The UAV on which this survey is based belongs to the MIDI cathegory, whose main views are shown in Figure 1.

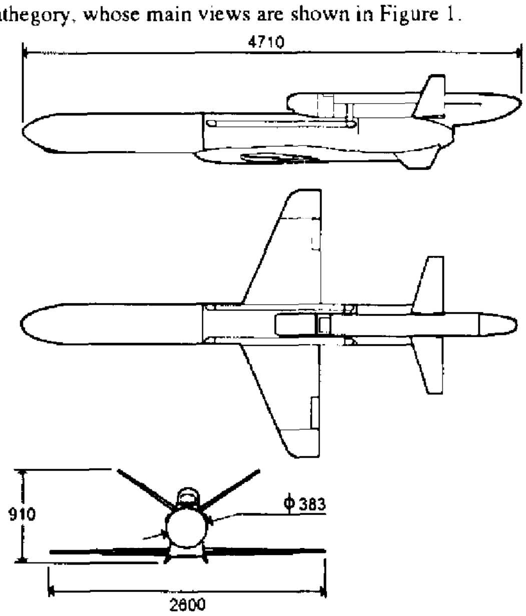


Figure 1: M-150 main wiews.

The air vehicle features a round fuselage containing the payloads, fuel tank and the engine, which is a turbojet engine with low by-pass ratio; above the fuselage is located the air in-take. The wing, located in the backward section of the fuselage, has thin sections, positive sweep on the leading edge and null sweep on the trailing edge, low aspect-ratio and

Paper presented at the AGARD MSP Symposium on "System Design Considerations for Unmanned Tactical Aircraft (UTA)", held in Athens, Greece, 7-9 October 1997, and published in CP-594.

ailerons for control on the roll axis; the main feature of the air vehicle is its unconventional tail, which is in form of a V; the movable part of this tail can be controlled only with symmetrical motion, to obtain control on the pitch axis (it functions as an elevator), the turning of the vehicle is obtained only by rolling the plane with the ailerons.
The mathematical model has been developed from a data-base documenting every single subsystem; it was modelized:
Aerodynamics,
Mass properties,
Turbojet engine,
Actuators group,
Avionic sensors: Attitude and Heading Reference System (AHRS), Air Data Computer (ADC), Global Positioning System (GPS),
External environment.

3. MATHEMATICAL MODEL, MOTION EQUATIONS AND THEIR LINEARISATION

The differential equations describing an airplane motion, in their most general form, are composed of a system of nine equations and nine unknowns; this system has been explicitated and re-written to present every single unknown in only one equation, so it is possible to solve each equation separately with numerical methods like the Adam-Bashford 2nd order one.
The differential equation system might be furtherly simplyfied considering a series of hypotesis on the airplane and the variables which perturbate its trim status; this operation is called linearization of the motion equations. The starting point for this operation is a steady trim condition for the airplane, around which it will be evaluated a simplifyed desciption of its evolution. The steps to write the motion equations and for the following linearization are here exposed:
I The airplane is considered as a stiff body.
II The airplane mass and its distribution are intended steady.
III The airplane holds the XZ plane as a symmetry plane.
IV The gyroscopic effects of all the moving rotors (compressor and turbine stages) are considered irrelevant into the motion equations.
V The airplane is supposed in a steady state and the parameters of this state are perturbed by little variations.
VI The motion in the longitudinal plane is not influential over the motion into the lateral-directional plane and vice-versa (uncoupled planes).
VII The environmental parameters variations are considered irrelevant if the altitude variations of the airplane are small during the motion.
VIII The turbojet thrust is supposed to be aligned with the X body axis.
With the linearization operation a system of linear differential motion equations is obtained, from this system it is possible to represent the motion by a first order differential equations system called the "status equations", in which the principal and most interesting parameters are explicitated. The status equations, disassembled into separate equations and explicitated for the parameters under evaluation, give the *transfer functions*, by which it is possible to study the architecture of the control system.

4. SAS DEVELOPMENT

The SAS is that part of an aircraft Autopilot (historically the first to be realized) that damps oscillations around pitch, roll and yaw axes by means of contrasting aerodynamic moments produced by rotation of control surfaces.
On the ground of aircraft configuration, SAS damps and possible disturbs: in the linear model each of the damper loops are separately studied (see ref. 1 for further details). Then the two loops are studied by means of root locus, polar and Bode diagrams to estimate their stability; the Gain and Phase margins are evaluated both on Bode and polar diagrams (by means of Nyquist principle).
When the most satisfactory feedback design is defined, this will be optimized by implementing it in the aircraft linear and 6DOF models over the whole flight envelope.

4.1 Pitch Damper (Longitudinal oscillations damper)

The device acquires body-axes pitch rate q and opposes it in case of high-frequency oscillations, instead it keeps idle in case of null or low-frequency oscillations; Pitch Damper works by means of elevator and so the $q/\delta e$ aircraft transfer function will be used for estimating the Damper performance.

4.2 Roll Damper (Lateral oscillations damper)

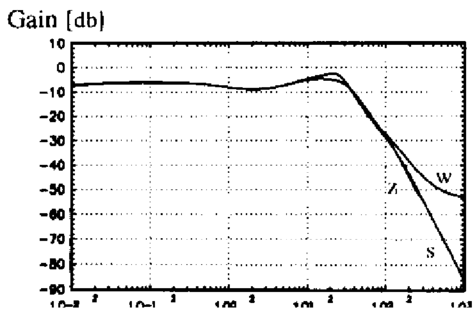
The device acquires oscillations of body-axes roll rate p and opposes it by means of asymmetrical manoeuvre of ailerons in case of high-frequency oscillation, therefore $p/\delta a$ aircraft transfer function will be used for estimating the Damper performance.

4.3 Z and W transfer function analysis

Control loops analysis and synthesis in linearized system has been founded on continuous transfer function in s complex variable, that is Laplace transform.
To obtain a better confidence in the analysis made by means of Laplace transforms, confidence already obtained comparing linearized model and 6DOF model, z and w transfer function analysis has been performed.

4.4 Pitch and Roll damping loops

Investigating the responses of the two damper loops that are part of the Autopilot, it can be reported that sufficient damping ratio and sufficient response rate have not been achieved, in spite of optimization of time constants.
One of the possible solutions concerns a second feedback loop of the quantity controlled by Dampers. It has been chosen for its advantages: it is simpler to realize and less burdensome for the AP microprocessor. The new outer loop, named Damping loop, is characterized by unitary gain and only one block for sensors simulation.
The transfer functions of these two loops have been analyzed too by means of Laplace transforms (s) and discrete transforms (namely z and w): the results of this frequency analysis is shown in Figure 2 and Figure 3 for Pitch and Roll Damping separately (see ref. 2 for further details).
Figure 2 shows the Bode diagrams (Gain and Phase) for Pitch Damping loop in s, z and w. Figure 3 holds the same for Roll Damping loop.



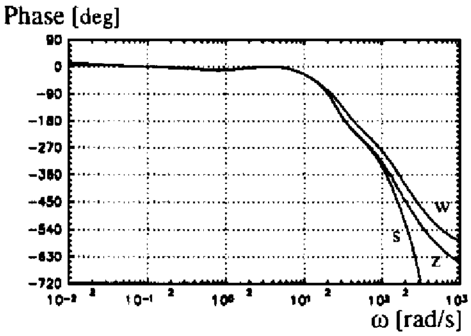


Figure 2: Pitch Damping frequency analysis.

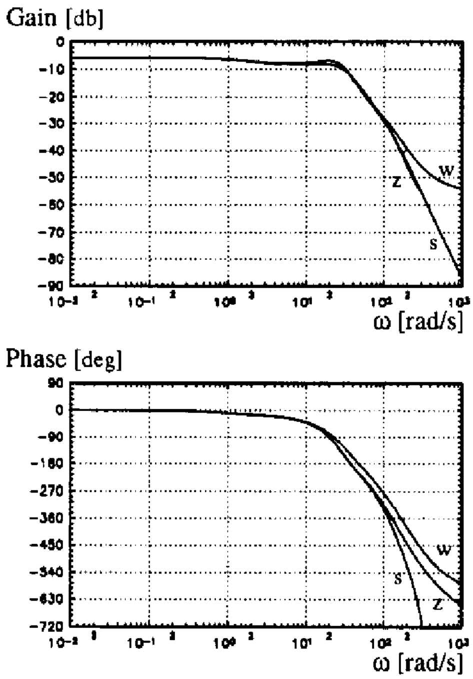
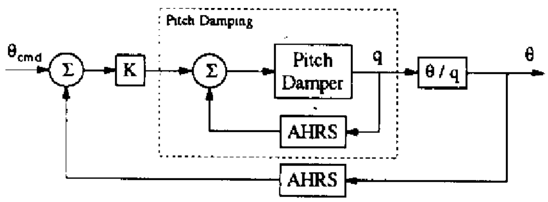


Figure 3: Roll Damping frequency analysis

5. ATTITUDE AUTOPILOT DEVELOPMENT

5.1 Pitch Acquire and Hold.

The device acquires and holds pitch angle: when the aircraft has to climb to achieve altitude or to level after a dive for example, the desired pitch angle is commanded from FMS/AP. Comparing commanded pitch angle with measured pitch angle, the input pitch rate *q demanded* for SAS is calculated (by means of a multiplying constant); in response to the SAS demand, an *actuated q* is returned, which (considering transfer function θ/q) will generate an *actuated* θ. Pitch Acquire and Hold loop, shown in Figure 4, is obtained by means of a feedback design of θ *actuated* that is measured by sensors separately (see ref. 2 for further details).



5.2 Roll Acquire and Hold

The lateral and directional channel is controlled by this loop that acquires and holds roll angle: since the conceptual design criteria for this operation are the same of Pitch Acquire and Hold control loop, the architecture and development methodology are the same too. In this case the ϕ/p transfer function has been taken into account.
The system Damper + Damping + Acquire and Hold obtained in this way, reduces the time to achieve regime condition and increases oscillations damping.

5.3 Control Laws optimization

Once the control loops have been designed, an optimization of the internal parameters is necessary to guarantee the best performances in the whole flight envelope. For this reason, evaluations both on linearized and 6DOF models have been thoroughly conducted.

6. STEERING AUTOPILOT

Once the attitude autopilot has reached its final design and has undergone evaluation tests, the steering autopilot can be dealt with.
In the Steering mode, the autopilot generates three commands: altitude, groundspeed and roll; to acquire and hold the commanded values of the flight parameters, a different loop for each has been designed. In the particular case of altitude, two different loops have been studied, implemented and tested: one for acquiring altitude, the other to hold it.
Given the measured flight altitude, a sector (with variable limits) above and under it has been defined: if the commanded altitude is within this sector, the autopilot activates the Altitude Hold mode, otherwise it reverts to Altitude Acquire mode. This differentiation comes from the necessity to guarantee flight safety over acquiring different altitudes in different flight conditions.
In the Altitude Hold mode, besides the altitude loop, the *groundspeed* and *roll acquire and hold* loops are contemporarily active; instead, in the Altitude Acquire mode, only the *roll acquire and hold* loop is active.

6.1 Altitude Hold loop

The *altitude hold* loop operates by means of the elevator to hold the commanded altitude. The starting point of the design process is the Vertical velocity / pitch rate transfer function, around which the whole linearized model will be built.
The *altitude hold* loop is made up of an inner loop (formally a damper loop) and of an outer loop (which is referred to as a position loop).
On analysing the linear inner loop, it can be found that is based upon the Vertical Velocity/q transfer function: to obtain the desired Vertical Velocity a Pitch rate is demanded, therefore (through the Pitch damping loop) an elevator rotation is commanded.
The outer loop is therefore based upon the h/Vertical Velocity transfer function.
In this way it is clear that, to hold a certain altitude (or to acquire an altitude not much different from the current one) the final command is an elevator one.

6.2 Groundspeed Acquire and Hold loop

The *groundspeed acquire and hold* loop, as the *altitude hold* loop, is composed of an inner loop and an outer loop.
The linear inner loop is based upon the Groundspeed

As it was foreseen by harmonic analysis, and later confirmed by 6DOF simulation, this is not a fast response loop, since the normal turbojet reaction time to a throttle command is not so quick.
Anyway it has been preferred a slower but more precise loop to a design which gave precedence to fast response, but which allowed Groundspeed oscillations around the commanded value. By the way this also helped to prevent compressor and turbine problems in the turbojet, related to sudden and violent shifts in throttle command.

6.3 Roll Acquire and Hold loop

The *Roll acquire and hold* loop here referred to, is the same described in the Attitude autopilot.

6.4 Altitude Acquire loop

The *Altitude acquire* loop has been designed on a completely different approach from the *Altitude hold*: first of all, the best climb and dive pitch attitudes have been evaluated, then on these grounds optimal climb and dive IAS have been calculated.
Once obtained the climb and dive speeds, it has been chosen to acquire and hold them by the elevator rotation. In this way, the necessary steps to climb or dive are: calculate the IAS commands (which are a function of the actual altitude), then acquire and hold them.

6.4.1 IAS Acquire and Hold loop

In order to achieve the correct climb or dive speed while effectively climbing or diving, it has been decided to achieve this velocity by means of elevator command.
Since the climbing speed is slightly lower than the IAS corresponding to the lowest programmable groundspeed, it's obvious that a slower velocity can be achieved only by climbing; similarly, since the diving velocity is only a few m/s above the highest horizontal velocity, to achieve this velocity the UTAV effectively dives.
It must be noticed that, to account for roll manoeuvres while in Hold mode, the lowest programmable groundspeed has been limited to a value slightly greater than the calculated stalling TAS for maximum roll.
Speaking of the actual loop design, it can be said that it is similar to the *altitude hold* loop: there are two nested loops.
The outer loop compares commanded IAS with actual IAS and, via a scheduled gain, demands an acceleration (IAS derivative); the inner loop compares the demanded acceleration with current one and, through another scheduled gain, demands a pitch rate which is given as input to the pitch damping loop.

6.5 Control Laws optimization

The optimization of the first three loops (*altitude hold, groundspeed acquire and hold, roll acquire and hold*) has been conducted on linearized model and then on the 6DOF model, as seen before for the Attitude autopilot loops.
The optimization of the *IAS acquire* loop, given its high degree of non-linearity, has been studied and optimized directly on the 6DOF model.

7. GUIDANCE AUTOPILOT

Once the main loops for the Steering Autopilot have been implemented, optimized and tested, the last part of the autopilot has been faced up.
To better understand the functional mode of the guidance The main phases of the M-150 flight are:

- Launch,
- Navigation (autonomous or remote),
- Recovery.

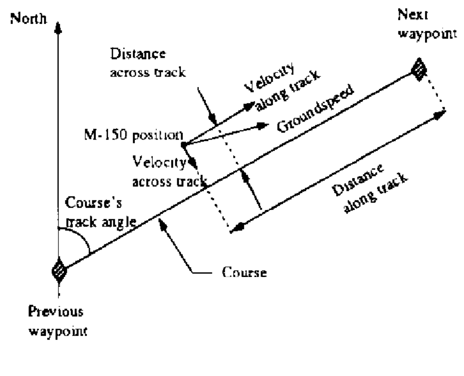
The Launch phase is intended to safely bring the plane to a preset minimum altitude and groundspeed from which start the mission. In this phase a preselected sequence of pitch and throttle commands are fed to the UTAV actuators, while the ailerons are kept neutral: the whole phase takes place in the longitudinal evolution plane.
Once the Launch phase is terminated, the FMS/AP switches to the Navigation phase and, if the autonomous mode is selected, the flight plan is brought to attention, and the autopilot performs the waypoints acquisition.
This operation is quite complex because there are several differen waypoint types: for the purpose of this study we will explain only type 1 and 2. Type 1 waypoint is the waypoint that must be overflown by the UTAV, then the autopilot can switch to the next one; type 2 waypoint means that the autopilot must link up the actual flight course (connecting the previous waypoint to the next) to the next one (connecting the next waypoint to the following) by turning (track connecting mode).
The Navigation phase might also be carried on by a ground operator: this is the remote mode. In this case the operator can fly the UTAV in Steering mode (altitude, groundspeeed and roll commands) or in Attitude mode (pitch, roll and throttle commands).
Once the last waypoint has been reached (if in autonomous mode) or the recovery command has been sent from the ground operator (if in remote mode), the UTAV disposes itself to be recovered.

7.1 Track Acquire and Hold

Once a waypoint is reached, a new course has to be initialized: by means of latitude and longitude of the previous and next waypoint, plus the spherical correction for the earth's surface (performed according to WGS 72 or WGS 84 earth's models), the actual course's track angle and the direction cosines are calculated. Then, the following navigational parameters are routinely updated:

- Distance along track: the distance, along the line representing the course, from the actual position to the next waypoint.
- Distance across track: the distance from the actual position and the line representing the course.
- Velocity along track: the actual velocity along the line representing the course.
- Velocity across track: orthogonal velocity to the previous one.

Figure 5 better explains the meaning of these parameters.



The *track acquire and hold* loop is again constituted by an outer loop (position loop) and an inner one (velocity loop).
The outer loop compares the actual distance across track with the desired one (which is 0), and generates (via a scheduled gain) a velocity across track demand.
The inner loop compares the demanded velocity across track with the actual one and generates an appropriate roll command.
The distance along track parameter is evaluated to switch waypoints when it becomes 0 or negative.

7.2 Track Connecting mode

The Track Connecting mode is an intermediate phase between two consecutive courses. When the next waypoint is a *type 2* one, the FMS/AP calculates a turn radius from actual TAS and maximum allowable roll.
Given the turn radius, the distance from the next waypoint (reached which the turn is commanded) can be calculated.
While holding the same commanded altitude and groundspeed of the approaching waypoint, the FMS/AP commands maximum roll to achieve the next course, pointing towards the following waypoint.
This turning state is held until the next course is reached, then the new waypoint's parameters can be brought to attention.

8. ATMOSPHERIC TURBULENCE

For testing the performances of the Autopilot, a model of the statistic turbulence has been implemented as part of the external environment.
Statistic turbulence has been studied by means of Dryden model according to MIL-F-8785/C norm; aircraft has been specifically tested in moderate turbulence alongside the three earth-axes and around the three body-axes for p, q, r angular rates. Diagrams of the perturbation linear velocities (along earth axes) are shown in Figure 6 through Figure 8 .
The performances achieved through turbulence have been compared with flight in calm atmosphere.

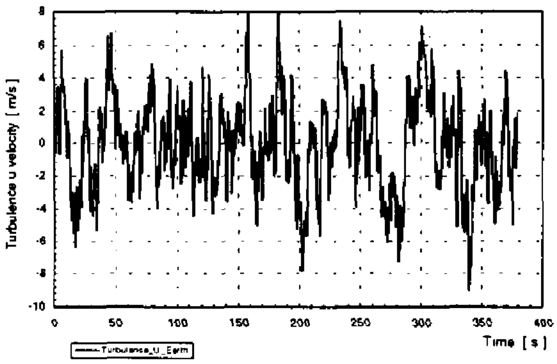


Figure 6: Atmospheric turbulence velocity u

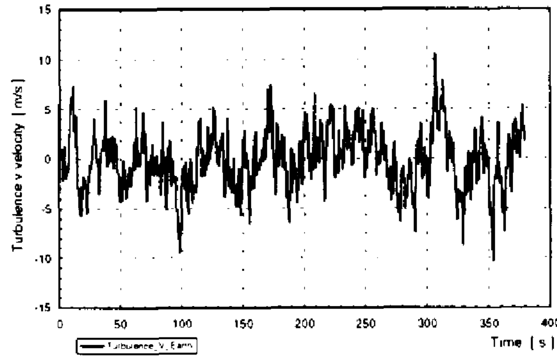


Figure 7: Atmospheric turbulence velocity v

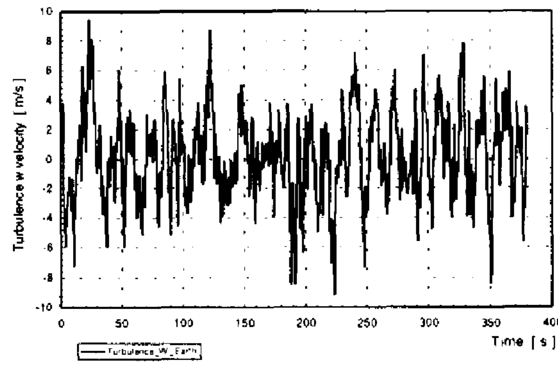


Figure 8: Atmospheric turbulence velocity w

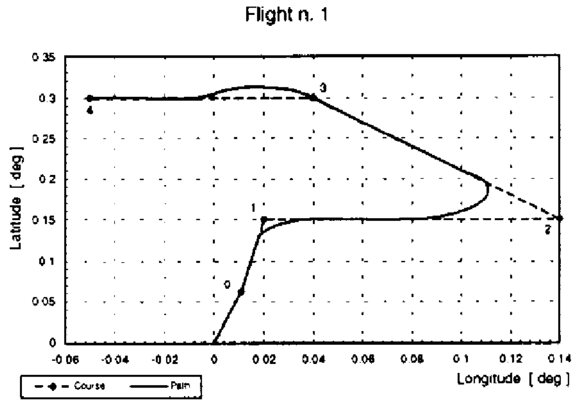
9. UTAV SIMULATED FLIGHT TESTS

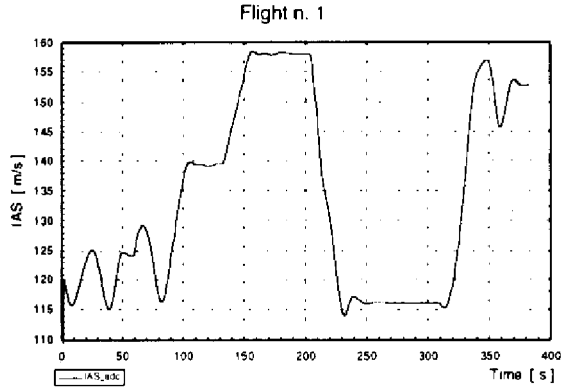
To evaluate the performances of the FMS/AP in its final design review, a series of simulated flight tests have been conducted with various flight plans. Here reported are two similar flights which have been conducted in autonomous mode: the only difference between the two flights lies in the added atmospheric turbulence on flight no. 2, to better evaluate performances in non-ideal flight conditions.
The flight plan (common to both the first and second flight) is the following:

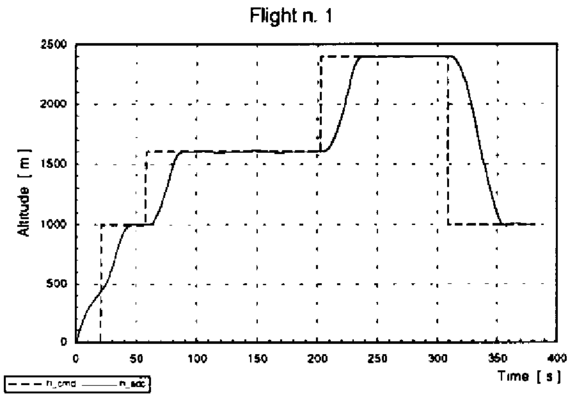
- Launch from an altitude of 0 meters a.s.l. with 10° heading orientation.
- Transition to safe manoeuvre flight condition: 1000 m height above launch altitude and minimum groundspeed of 130 m/s. This must be accomplished disregarding of the route (towards first waypoint) track angle.
- First waypoint acquisition: type 2 waypoint, 0.15° latitude North, 0.02° longitude East, 1600 m altitude, 150 m/s groundspeed.
- Second waypoint acquisition: type 2 waypoint, 0.15° latitude North, 0.14° longitude East, 1600 m altitude, 170 m/s groundspeed.
- Third waypoint acquisition: type 1 waypoint, 0.30° latitude North, 0.04° longitude East, 2400 m altitude, 130 m/s groundspeed.
- Fourth waypoint acquisition: type 1 waypoint, 0.30° latitude North, 0.05° longitude West, 1000 m altitude, 160 m/s groundspeed.
- Istantaneous recovery.

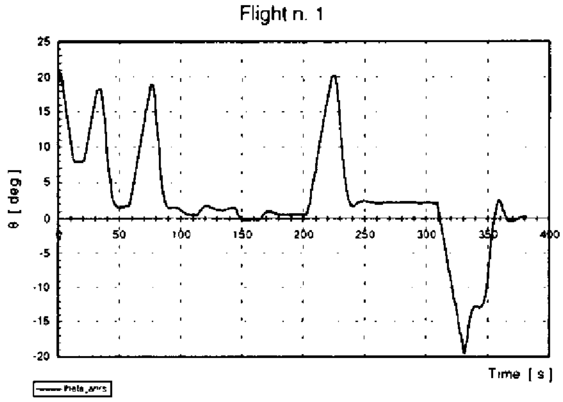
The 0 point in the Latitude vs Longitude charts indicates the flight conditions described before have been reached.

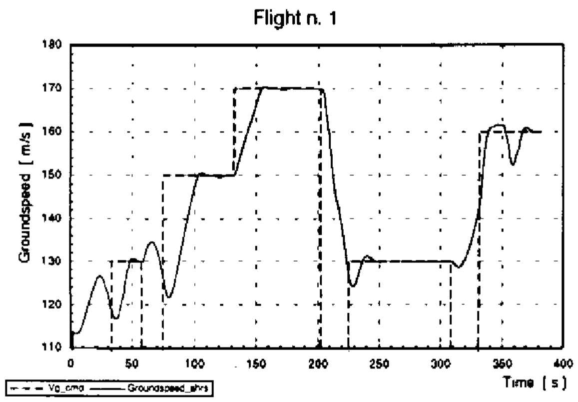
9.1 UTAV Test flight no. 1

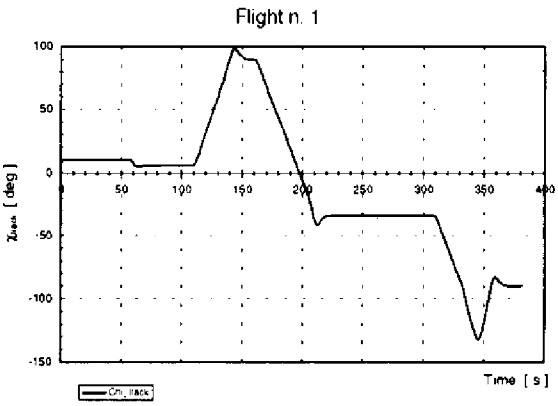


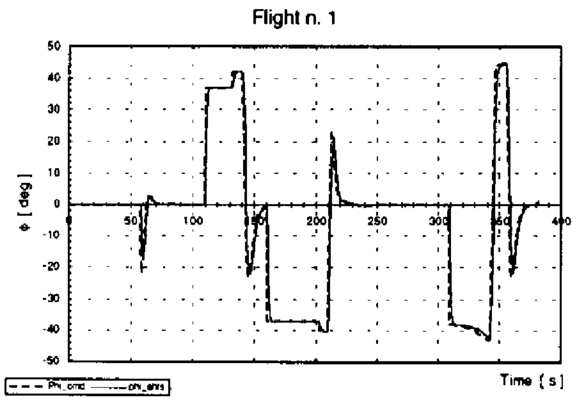


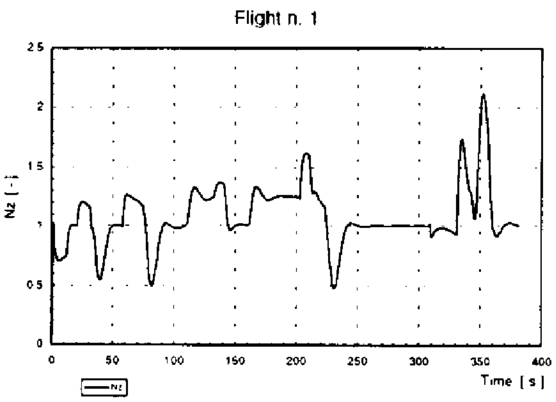




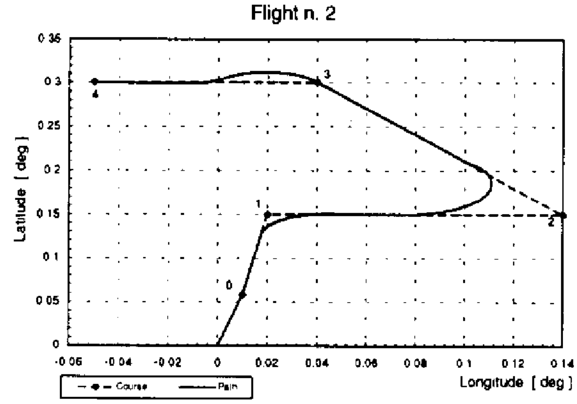


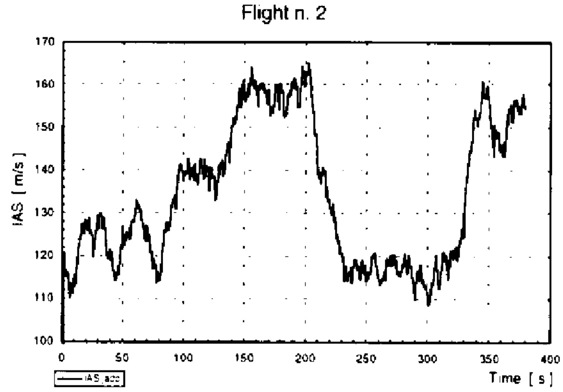


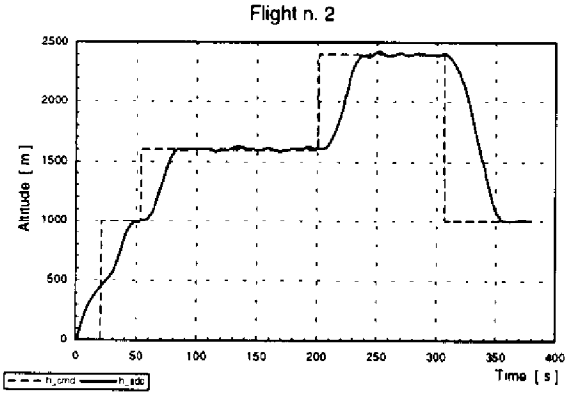


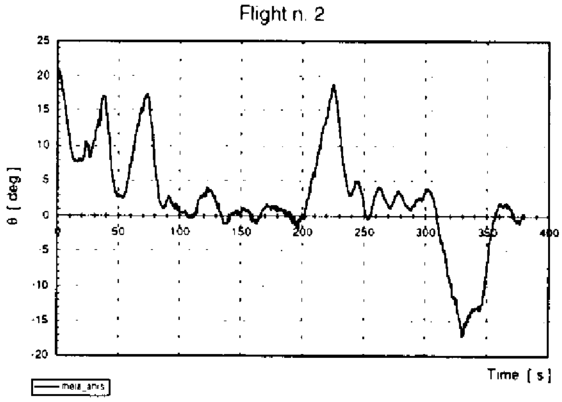


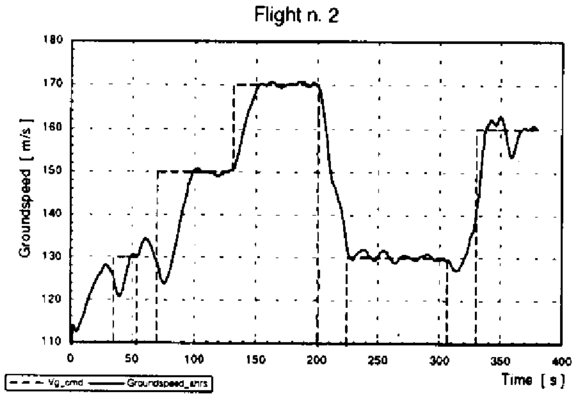
9.2 UTAV Test flight no. 2

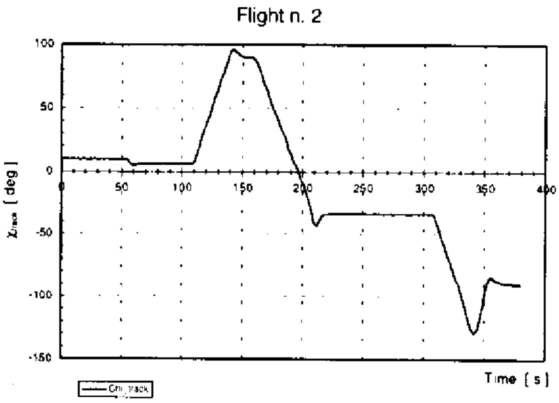


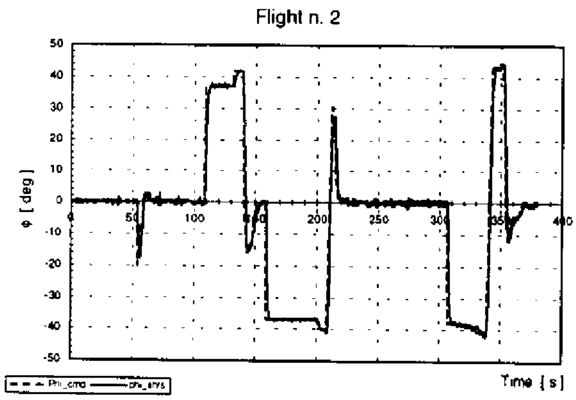


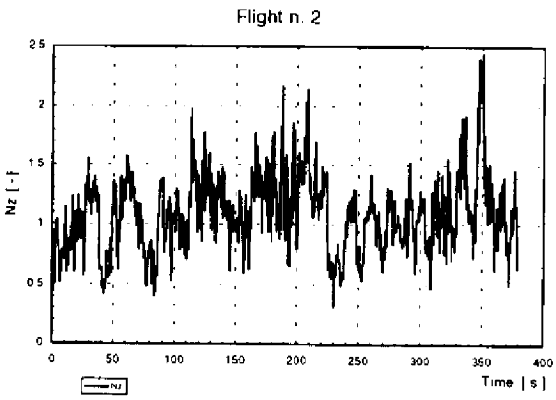












10. RIG - AIDASS FOR M-150

Once completed the design phase of every single sub-system for the M-150, a special tool called Rig has been built to perform ground integration tests and performance evaluations of the real UTAV in a real-time environment.
This Rig has purposely been designed to help in performing the difficult task of integrating the on-board avionic in a step-by-step process: it is in fact possible to simulate those sub-systems and equipments which are intended to be integrated in further steps, allowing at the same time the full functionality of the UTAV avionics.
Rig is made up of a bench and an AIDASS, which stands for Advanced Integrated Data Acquisition and Simulation System.
The bench is composed of a mechanical structure and wirings: the mechanical structure supports all the patch panels of the system channels, the airframe and the equipments, while the wirings allow all the Rig electrical connections.
The AIDASS is a ground equipment simulating the external environment and all the avionic equipments of the UTAV, while collecting all the internal and sensor parameters, it is composed of a mainframe computer (a VAX 6000 computer), a workstation to allow man-machine interface, and an input-output driving system called Front/End.
The whole assembly is better explained in Figure 9.

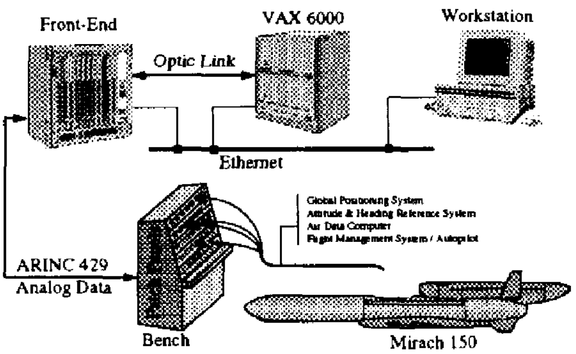


Figure 9: M-150 Rig-AIDASS

On the VAX computer the whole 6DOF mathematical model of the M-150 is implemented as well as the avionic equipment and external environment modelization, while the Front/End manages the whole input-output cards and the data acquisition and recording; the workstation is used to manage and monitor the whole AIDASS and avionic sub-systems functioning.
The peculiarity of the Rig assembly is that it allows real-time simulation and stimulation of the Mirach 150 UTAV; the only drawback is that some avionic systems won't give dynamic output.
For example, since the UTAV lies on a bench, the AHRS sensed parameters (such as linear and angular velocities, attitude angles, geographical position etc.) won't be consistent with the simulation in progress, so they will be substituted (always in real-time) by the calculated ones from the sensors mathematical model running on the VAX computer.
The main advantages of this Rig can be summarized as follows:

- The whole Avionic System can be integrated and tested, and its performances evaluated.
- The programmed flight plan can be ground executed to be
- The flight clearance can be delivered.

11. CONCLUSIONS

The reported work shows that the methodology of Autopilot control laws design criteria, followed by authors, are correct and effective; even if in the peculiarity of the problem that has been taken into consideration, used criteria acquire a significant generality from the methodology point of view and go beyond the specific shown case and are a useful guidance for solution of similar problems.
Upon examinating the Autopilot performances, the included charts show that good damping ratios and response rate for the SAS have been achieved, while the acquire and hold loops (both of the Attitude and Steering Autopilot) perform the commands acquisition in a flawless manner, in spite of mantaining a simple structure. The Guidance Autopilot too shows the same behaviour, even in the case of atmospheric turbulence.
The Rig integration and real-time simulations with hardware in the loop, provide the necessary confidence on the Autopilot performances and the compulsory flight clearance to start the flight tests.

12. REFERENCES

1. L. Borello, P. Faggion, L. Zolla: "Progetto di un sistema di aumento di stabilità + autopilota per velivoli non pilotati", 38° Convegno ANIPLA, Atti del convegno, Perugia (Italy)1994.
2. G. Bertoni, L. Borello, P. Faggion, S. Vallino, L. Zolla: "Autopilot synthesis for unmanned air vehicles", 1995 IFAC-IACA Conference, Bejing (Rep. of China), final printings.
3. Beal, T.R. (1993). Digital simulation of atmospheric turbulence for Dryden and Von Karman models. *Journal of Guidance, Control and Dynamics*, Vol. 16 No. 1, pages 132 - 138.