Presentation of the MAVDEM project

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MAVDEM (Miniature Air Vehicle DEMonstrator) is a project funded by the European Defense Agency. This is a three year project and the consortium is composed of French (ONERA and Alcore Technologies), Spanish (SENER), Italian (Oto Melara and Celin Avio) and Norwegian (TellMie) partners. The objectives of the project are to define, build and flight-test a MAV configuration (less than 50 cm wingspan) able to perform infantryman support missions. The technical requirements are based on two major capabilities: stationary flight and economic fast cruise. As these two objectives are conflicting, vehicle configuration is a key point of the system design. Nevertheless, all the aspects of a MAV system are taken into account, from the propulsion system to the Ground Control Station.

I. Introduction

MAVDEM[1] (Miniature Air Vehicle DEMonstrator) is a project funded by the European Defense Agency. This is a three year project and the consortium is composed of French (ONERA and Alcore Technologies), Spanish (SENER), Italian (Oto Melara and Celin Avio) and Norwegian (TellMie) partners.

The objectives of the project are to define, build and flight-test a MAV configuration (less than 50 cm wingspan). This MAV should be capable of stationary flight and economic fast cruise in order to perform infantryman support missions. An example of such a mission is open-field observation. In this mission, the MAV flies permanently above a given area in order to monitor the overall situation of the place, checking dangerous sites. Another type of mission is city exploration. In this case, the MAV is used as a scout in order to detect threats in an urban area. These threats can be vehicles or patrols as well as snipers hidden in buildings.

In order to perform such missions, this MAV has to combine two capabilities:

- Stationary flight, in order to look inside a building through windows, for example;
- Economic fast cruise, in order to cover the maximal area in a minimum of time, with the maximal endurance.

Those two objectives are conflicting and require making the right trade-offs, in order to meet the requirements in terms of endurance and velocity.

Indeed, these requirements are pretty challenging:

- Endurance requirement: 15 minutes of stationary flight and 30 minutes of economic cruise;
- Velocity requirement: 20 m/s as maximum speed.

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II. Project methodology

The methodology of the MAVDEM project is based on the common process for designing a system. The process is divided into four, clearly defined phases, illustrated in Figure 1.

Preliminary Design Phase

This phase includes the identification and the analysis of the User requirements in order to define target missions. A system functional analysis is then derived and is used as a basis for the system architecture definition.

A technological state of the art analysis is performed in order to identify potential solutions for the demonstrator, especially from an aeroshape configuration point of view.

Once all potential concepts are identified, a selection process enables to perform a first selection in order to keep only 2 configurations after the Preliminary Design Review (PDR).

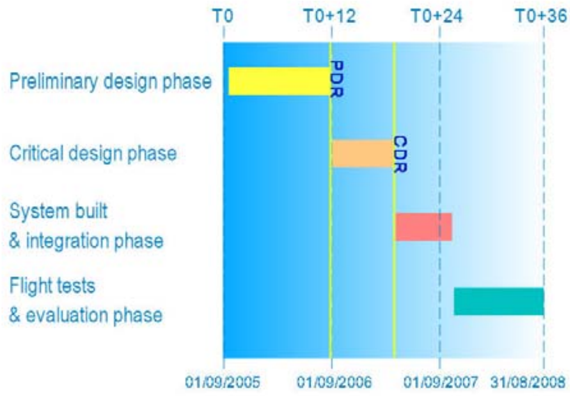

Figure 1. MAVDEM project phases

Critical Design Phase

This phase includes a detailed design of the system, based on a precise description of each sub-system. Then, a detailed analysis of the 2 remaining concepts is performed in order to select the final demonstrator concept, during the Critical Design Review (CDR).

System Build & Integration Phase

During this phase, the different sub-systems and components are procured, manufactured, built and finally integrated into a complete MAV system.

System Test & Evaluation Phase

Once the demonstrator system integration and the airframe manufacture are finished, flight tests can be performed for the system evaluation.

After the test phase, the analysis of the results is done. Recommendations can be made in order to close the design loop: technical requirements and applicable missions may be slightly different from what was expected at the beginning of this research programme.

III. Missions identification

The identification of the missions is based on the definition of two basic scenarios:

- Scenario 1, the MAV should fly at maximum cruise speed and inspect in detail, in stationary flight, some targets located at maximum distance away and then fly home at maximum cruise speed. (Focus on the combination of fast cruise and VTOL/stationary capability)
- Scenario 2, the MAV should act as a scout for a small unit in an urban scenario. Fly ahead of soldiers, inspect roofs and look through windows. Endurance between 15 and 30 minutes. (Focus on slow/stationary flight)

Derived from these basic scenarios, two types of missions have been identified and described:

- The demonstration missions were used as a basis to define the flight tests campaign; they are made to validate the required performance of the MAV demonstrator in terms of endurance, speed, manoeuvrability, data link, etc;
- Moreover, future operational missions were investigated to assess the possible application areas for the future MAV. They are numerous in the military and civil fields (law enforcement, scientific or commercial applications, etc.). However, these future operational missions will not be tested.

IV. System architecture

The identified MAV missions' requirements enable to perform a functional analysis from which the system architecture was derived.

This system architecture is described in Figure 2.

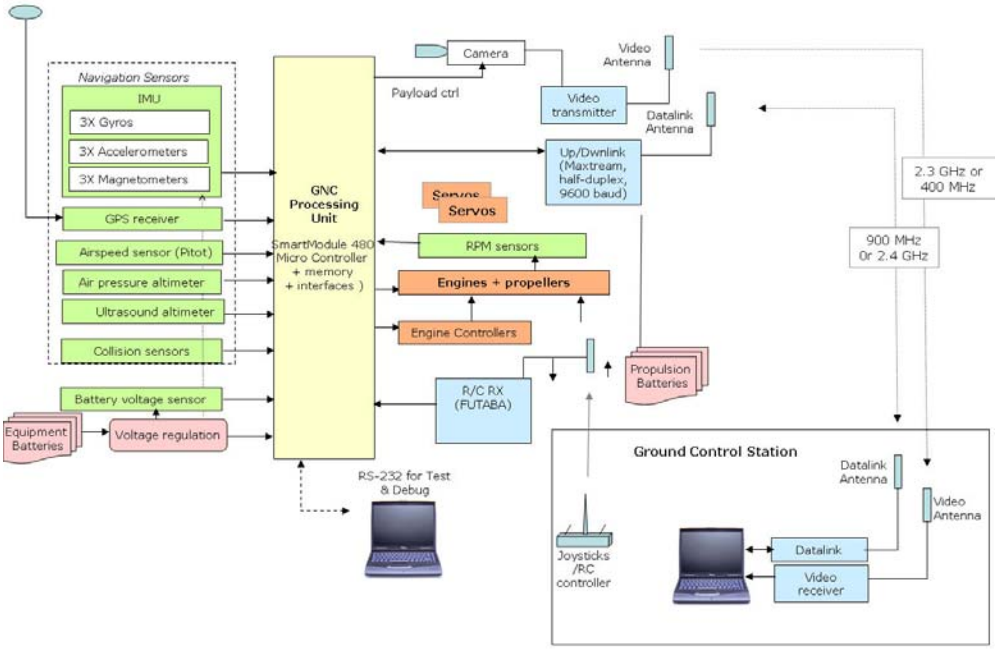

Figure 2. System architecture

This architecture is not specific to a precise aeroshape configuration. The only parameters depending on the MAV configuration are the number of engines, servos, controllers, etc. Such architecture can be used whatever the selected configuration is.

V. Vehicle configuration selection

As mentioned previously, the project methodology is to have a look at all kind of concepts potentially able to meet the contract requirements: stationary flight and economic fast cruise capabilities. Indeed, the purpose of this methodology is to consider all potential solutions in order to be sure that no possibility is missed, especially the best one! This also enables selecting concepts that are really and fully adapted to the requirements, not only partially.

The other aspect of such a methodology is to ensure a justification and documentation of all the choices made, based on a fair comparison of the solutions.

A. Candidate concepts survey

The first action of the vehicle configuration selection has been to make a survey, as wide as possible, of the existing VTOL concepts. During the preparation of this survey, ideas arose and new original concepts were designed within the consortium. These new designs were added to the survey list.

All the identified or designed concepts were defined by illustrative pictures, but also by the way to control the vehicle along all 3 axes (yaw, pitch and roll), in order to fully understand how each concept "works".

After this survey, 26 different concepts were identified, from 7 main categories:

- Four rotor concepts;
- Helicopter concepts;
- Single ducted rotors concepts;
- Double coaxial rotors concepts;
- Double tandem rotor concepts;
- Tail-sitter concepts;
- Tilt-rotor concepts.

As the purpose of this survey was to select, during the PDR, 2 configurations to be more investigated, it has been decided to perform a multicriteria analysis in order to sort the identified concepts.

Nevertheless, 26 different concepts have been identified. So, it was decided that performing a complete multicriteria analysis on 26 elements (with a high number of criteria, most based on calculation, in order to down–select two concepts at the PDR) was not the most efficient method. This is why it has been decided to perform this multicriteria analysis in two rounds: first to select 5 concepts and then 2.

B. High level selection

A first selection round with numerous concepts, but a low number of criteria has been performed. This selection was based on a limited number of criteria, not based on calculation but on the expertise of the consortium. Criteria have been divided in 3 main categories: performance, controllability/stability/manoeuvrability and safety.

This first selection round enabled to down select 5 concepts.

C. Preliminary design

After this first selection, the level of detail of these concepts has increased, in order to perform second selection aiming at keeping only two concepts.

This design improvement required several tasks:

- Identification and characterisation (weight, dimensions and power consumption) of the required onboard components;
- Propulsion considerations, especially on batteries volume and motors efficiency;
- Aeroshape design refinement, with associated estimated lift and drag;
- Performance estimation, based on the previous results.

1. Onboard components

Required onboard components have been identified from the system architecture. Commercial Of The Shelf (COTS) equipments that could possibly be used were identified and characterized in terms of dimensions, weight and power consumption.

The purposes of this task were:

- to try to create a "real" fuselage in which all those equipments could fit;
- to make a first estimation of the global power consumption, and so of the necessary batteries quantity;
- to make a first estimation of the overall vehicle weight, for performance calculation.

2. Propulsion

Based on the estimation of the weight and power consumption, the weight of the batteries was determined.

The hypotheses were:

- The batteries are supposed to be based on the technology available in 2008, which means LiS batteries of 500 Wh/kg.
- These batteries should enable the vehicle to perform **30 minutes of stationary flight**. Indeed, in order to start the loop process, this hypothesis is *a priori* majoring the 15 minutes of stationary flight and the 30 minutes of economic cruise.

Hypotheses were also taken considering the motors efficiency.

3. Aerodynamics

Based on the onboard components and batteries volumes, the fuselages of the configurations were modified so everything can fit within.

These new external shapes were studied through Computational Fluid Dynamics (CFD) calculation in order to give rough estimations of their lift and drag characteristics.

4. Performance

Performance calculations were performed, based on the vehicle weight and shape (CFD results), in order to verify that the endurance and maximum speed requirements were met. Several optimisation loops have been necessary.

All these aspects were taken into account in order to enhance the design of the 5 remaining vehicles. A second selection round was performed (based on these enhanced designs), in order to keep only 2 concepts for the next phase: the critical design phase.

As for the first selection, this second one was based on a multicriteria analysis; but this time, more criteria have been considered, including objective attributes (results of calculations). For this analysis, and in accordance whit the Customer, a strong importance was given to mechanical complexity and manoeuvrability; the other criteria were considered to be less important.

The results of this multicriteria analysis led to the following statements: the configurations that had a good ranking considering the performance criteria (maximum velocity, endurance…) had a bad ranking concerning the general criteria (complexity, control…). The opposite is also true.

According to the multicriteria analysis results, it appeared that 3 configurations should be further investigated for the next phase of the project:

- The first one was ranked first concerning the general criteria (high manoeuvrability, low mechanical complexity), but was last concerning the performance criteria (low lift provided by the fuselage, high drag);
- The second one was ranked first concerning the performance criteria (best performance in hover and cruise, good manoeuvrability), but was last concerning the general criteria (high complexity of the rotor hub, questionable yaw stability);
- The last one was daring (high complexity of the structure and shape, anticipated vibrations of the lifting surfaces), well balanced configuration (fair performance, decoupling mechanisms of the 2 rotors), reflecting the ambitions of this research project.

The retained philosophy was to combine the best properties of these 3 configurations in two options of configurations:

- 4 rotor concept for low mechanical complexity and easy manoeuvrability, and featuring a low drag fuselage. This is the resulting **configuration A**.
- Double coaxial rotors concept with low drag fuselage for high performance but with a simplified mechanism. This is the resulting **configuration B**.

D. Detailed design

Configuration A and configuration B designs have been improved and detailed in order to select the final prototype configuration. This design improvement was based on several aspects:

- Propulsion tests;
- Structure and internal arrangement definition;
- Aerodynamics.

1. Propulsion tests

One of the first actions has been to perform experimental propulsion tests (motors + propellers). The purpose of these tests was to get “real values” of power, efficiency, torque, current, etc. in order to choose the best motors and to optimise the propulsion system: rotor diameters and pitches, motor rotation speed, direct drive or gear box, etc. The results of the tests would also be used in order to “calibrate” the performance calculation algorithms.

In order to perform these experimental tests, the Alcore test bench has been used (Figure 3).

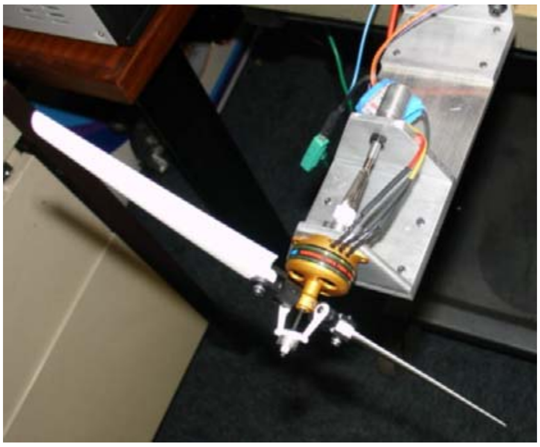

Figure 3. Propulsion test bench

For each configuration, several propulsion systems have been tested: various motors and propellers.

These experimental tests were very useful for the choice of the retained concept.

2. Structure and internal arrangement

Up to this stage of the project, the structure and internal arrangement of the various components were not precisely taken into account in the vehicle design. To consider them enabled a more detailed definition of both configurations.

Configuration A

Considering the configuration A, and in order to obtain a vehicle that could be transported in a restricted volume, the four propulsion sub-assemblies (motor, propeller, controller, motor support and arm) have to be dismounted quite easily from the central mast. Consequently, a connection based on a BNC-style hardware was selected. Such a component would allow simultaneously both mechanical and electrical connections. Given the current to be fed into the motors, rather large diameter pins should be considered, leading to rather bulky connectors.

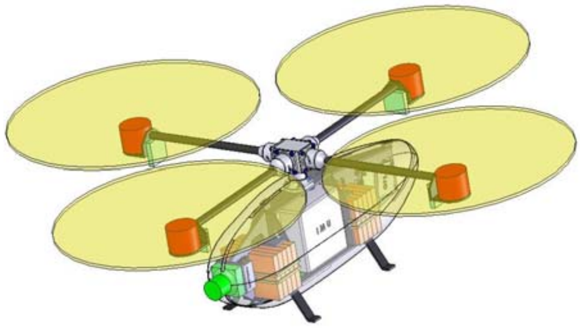

Figure 4. Configuration A detailed design

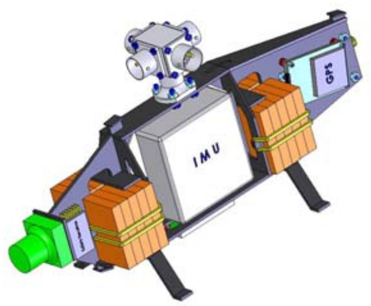

Figure 5. Configuration A structure and internal arrangement

Internal components arrangement has also been considered (Figure 5).

The battery packs are distributed around the two main components which are the Inertial Measurement Unit (IMU) and the processor. Each pack is maintained thanks to rubber band and parts of the structure which act as mechanical stops. Such a design would enable changing the size of these packs quite easily.

The fuselage is a shell made of two halves, which are connected to the main frame thanks to ¼ turn screws. The right half shell exhibits some extensions that "snap" on the left half, providing some additional clamping.

Configuration B

Considering the configuration B (Figure 6), one advantage of such a design is that the two rotor heads are mostly similar, which might be interesting from a maintenance point of view.

The fuselage (outer aerodynamic shell) is made of three parts, rear, centre and front. The configuration that is proposed for the structure is based on the hypothesis that the battery packs have to be changed on the battlefield, in order to successively perform several missions with different battery packs. Therefore, only the front part of the fuselage would be removed, the battery packs could then be extracted and replaced by new ones. This would enable flying another mission while the previous packs are being recharged. The details about the rear and central parts of the fuselage are not drawn. It could be imagined to have these parts divided into two halves, which would be connected thanks to screws on the front and rear fuselage supports which are bonded on the main structure. The details of the securing of the various parts of the fuselage on the airframe are not depicted. ¼ turn screws are considered, requesting minimum tooling to perform the battery exchange.

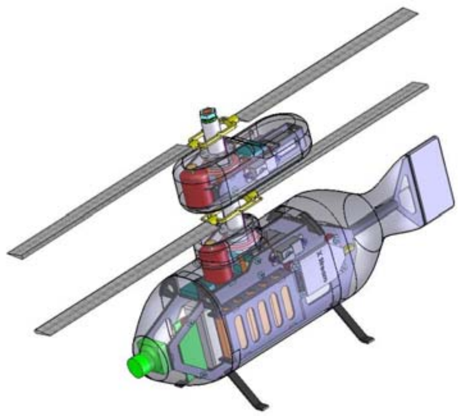

Figure 6. Configuration B detailed design

3. Aerodynamics

CFD calculations have been performed on each vehicle shape in order to get an estimation of their lift and drag characteristics. Drag has also been estimated as a function of the angle of attack.

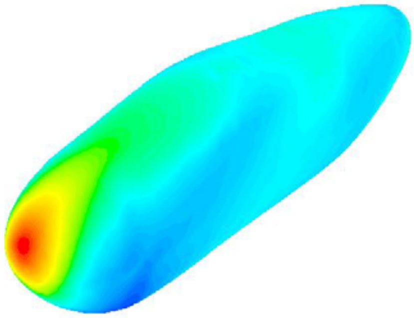

Figure 7. Example of CFD result on configuration A

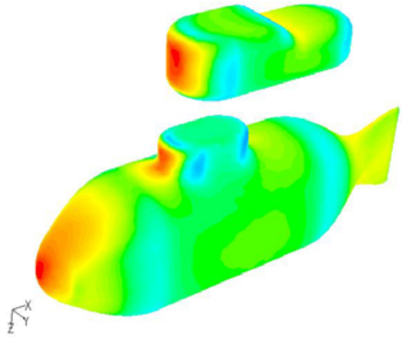

Figure 8. Example of CFD result on configuration B

4. Performance

A loop calculation of the estimated performance was made, based on the experimental propulsion tests, the improved mass budget (from the structure definition) and the aerodynamic analysis. This performance estimation was made for both configurations. It has been performed in terms of endurance, which is the most challenging and dimensioning requirement, especially concerning the propulsion.

E. Final choice

Taking into account all the previous information, a multicriteria analysis has been performed in order to select, between configuration A and configuration B, the system that will be built and flight tested in the following phases of the project.

Based on the multicriteria analysis results, and in agreement with the whole consortium, the retained configuration is **Configuration A**.

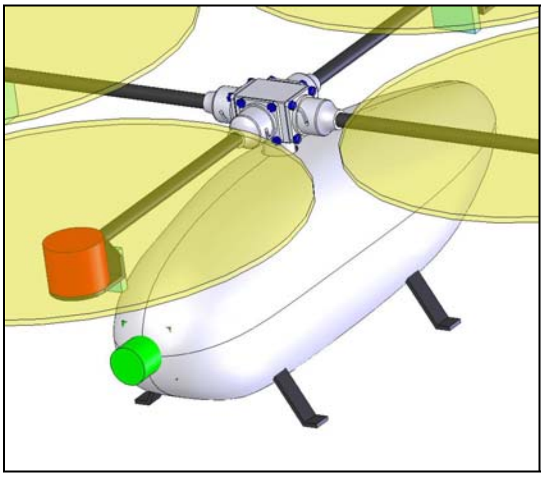

Figure 7. Selected vehicle configuration

VI. Guidance, navigation and flight control system

In parallel with the vehicles design, the work concerning the guidance, navigation and flight control system was running. The models used were generic in order to be independent of the selected vehicle configuration.

A. Guidance and control system

The guidance and control system was defined and a functional diagram was issued.

The function of the guidance and control (GC) system is to calculate the control values to be applied to actuators to maintain the stability of the aircraft and carry out the mission, using the estimation of the state of the aeroplane and according to the operator orders and mission data.

This system could be split up into the two modules: “strategy” for the reflection and “command” for the action as showed in Figure 8.

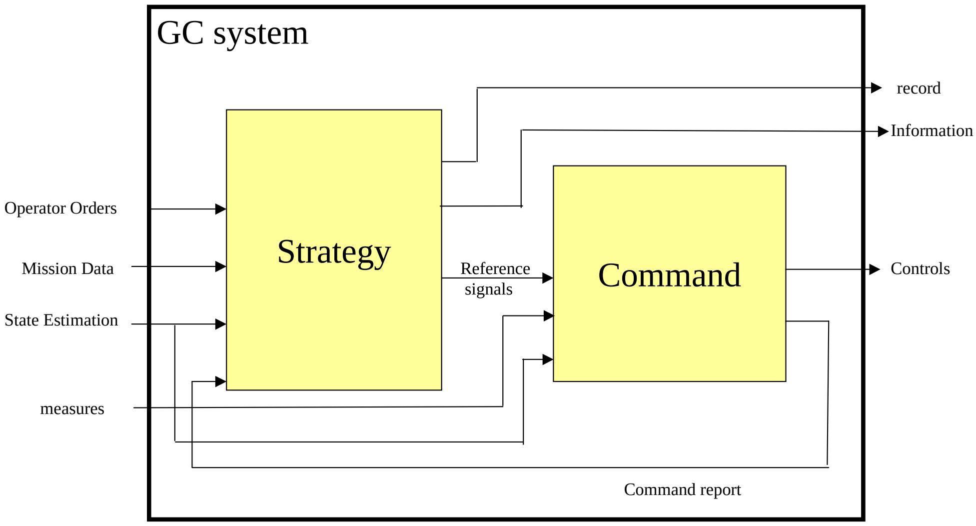

Figure 8. Functional diagram of the GC system

Generic mathematical models have been developed for the guidance and control and for the navigation.
The overall MAVDEM flight dynamics and control loops are illustrated in Figure 9.

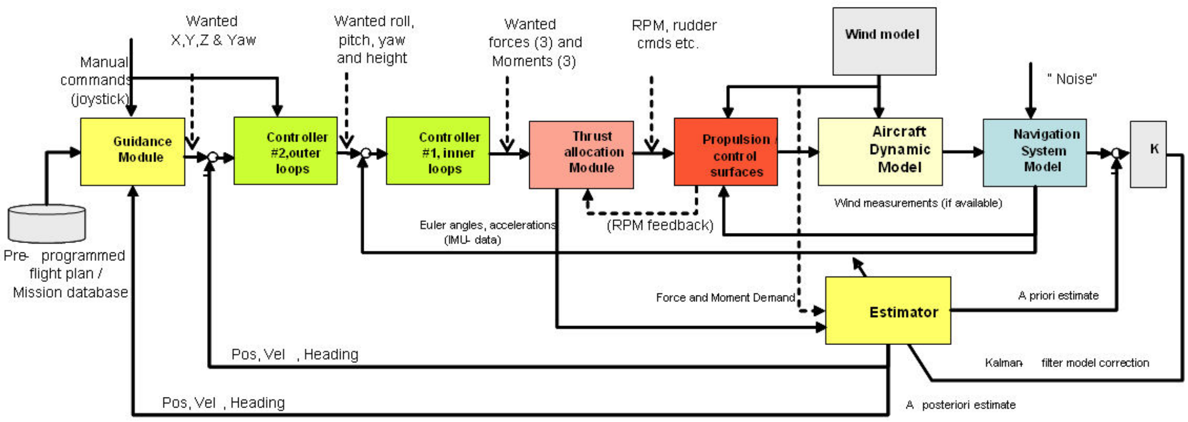

Figure 9. Guidance, navigation and control block diagram

B. Flight management

The various components of the flight management are illustrated in Figure 10.

Figure 10 presents the relation between flight modes and sub modes, and the transition among them. It can be observed that the manual mode is entered/exited through the stabilised manual sub mode.

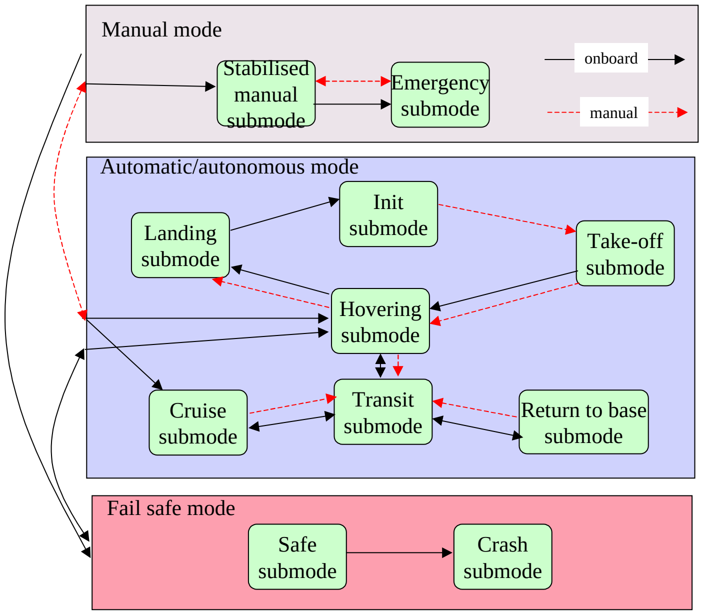

Figure 10. Flight management components

The transitions between modes and sub modes are also detailed in the diagram. The manual transitions are commanded by the pilot, while the onboard transition is decided by the GC software. The absence of manual transitions among the automatic/autonomous sub modes (except for return to base) does not preclude the pilot in automatic mode to perform all the activities associated to the different automatic sub modes. It rather avoids him/her the obligation to command the transition to a certain mode: the onboard software is then in charge of deciding such transitions depending on the pilot instructions and on the flight conditions.

Additionally, it can be observed in the diagram that the Failure Detection Isolation and Recovery function is active for all the sub modes. Should any failure be detected, a transition to safe sub mode would be commanded.

C. Simulation

Numerical simulations based on the flight dynamics characterisations of the MAVDEM UAV were developed.

The numerical simulator of MAVDEM was developed with one main objective, namely to design and test the navigation and control laws of the MAVDEM UAV. A secondary objective is to use a simplified model of the dynamics and guidance control logic in the Ground Control Station (GCS) for “Dry-Run” tests of the planned mission before the actual flight.

The natural selection of Software Engineering Environment (SEE) for the first main objective of the numerical simulator is Matlab/Simulink. This simulation tool has been made especially for that purpose and offers a great choice of utilities for the simulation and control design. The possibility of implementing automatically generated C-code into the embedded system could also be investigated and tested.

The secondary objective of the development of the numerical simulator is to use a simplified version of it in the GCS. The goal here is just to run quickly a simplified simulation of MAVDEM along the preplanned flight plan in order to check out the feasibility of the plan before the actual flight. As the GCS software will be quite GUI (Graphical User Interface) intensive and have a Microsoft “look and feel”, the natural SEE choice is Microsoft Visual Studio 2005, including SW languages like Visual C++, C# and Visual Basic 2005.

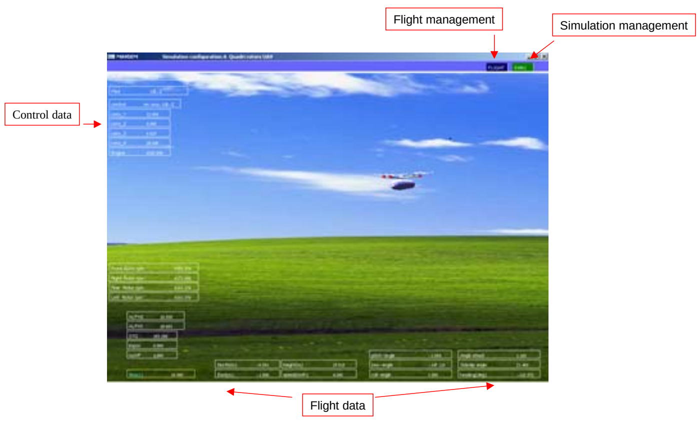

Figure 11. Simulator display

VII. Ground Control Station

The MAVDEM-GCS will be a hand-held, compact unit that can be worn over a protective vest or mounted on a tri-pod. The MAVDEM-GCS will unite a user-friendly software interface / GUI with advanced Real-Time control hardware. The goal is to allow even an inexperienced operator, with minimal training, to successfully control all phases of a MAV mission and to gather high-quality intelligence in real time.

The main functions of the GCS have been identified and a prototype of the GCS software has been developed (Figure 12).

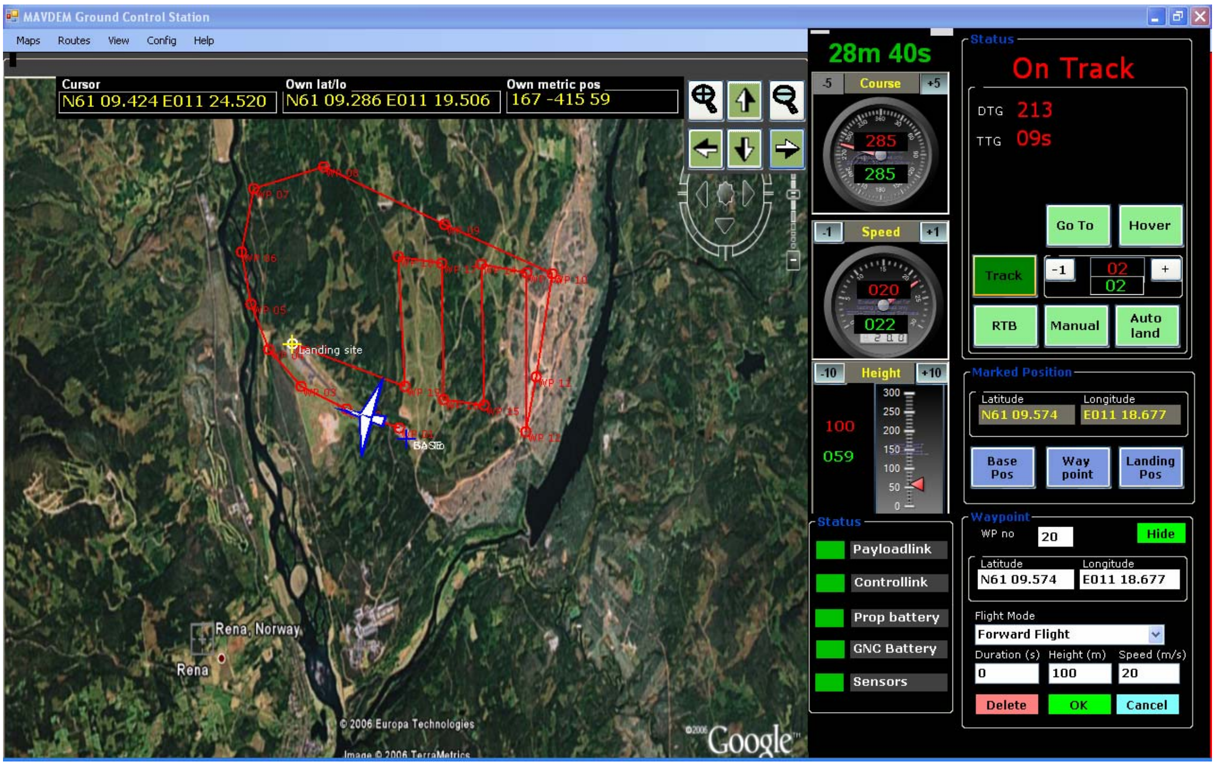

Figure 12. Ground Control Station prototype interface

The interface is really "user friendly" and intuitive: simple clicks on the map create the flight path.

Several automatic functions are already defined such as take-off and landing, flight paths tracking, etc. but also the manual mode.

Several other functions are still under development.

VIII. Conclusion

The MAVDEM project is now entering the "System built & integration phase". The manufacture of the vehicle structure, as well as the procurement of the main electronic components, has started. These elements will be soon distributed to all the partners, for integration purpose.

According to the current planning, the integration of the prototypes should start at the end of October 2007, and finish at the beginning of December 2007. Then the prototypes testing and assessment phase will start.

Preliminary flight tests are planned to be held in Spain during the first half of year 2008. Their purpose is to verify the MAV performance in "real" environment, in order to refine or correct unsatisfactory parameters.

The official flight demonstration will take place in the Rena military training camp in Norway during summer 2008. Its main purpose is to validate the MAV performance during outdoor missions.

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