Design Process and Real-Time Validation of an Innovative Autonomous Mid-Air Flight and Landing System

De Lellis E., Di Vito V., Garbarino L., Lai C., and Corraro F.

***Abstract*—**This paper describes the design process and the real-time validation of an innovative autonomous mid-air flight and landing system developed by the Italian Aerospace Research Center in the framework of the Italian national funded project TECVOL (Technologies for the Autonomous Flight). In the paper it is provided an insight of the whole development process of the system under study. In particular, the project framework is illustrated at first, then the functional context and the adopted design and testing approach are described, and finally the on-ground validation test rig on purpose designed is addressed in details. Furthermore, the hardware-in-the-loop validation of the autonomous mid-air flight and landing system by means of the real-time test rig is described and discussed.

***Keywords*—**Autonomous landing, autonomous mid-air flight, design and test approach, real-time hardware-in-the-loop validation

I. Introduction

In recent years, the use of real time with hardware-in-the-loop simulation assumed a growing importance in design and realization of guidance, navigation and control systems, in order to reduce time to market of these systems [1]-[4].This is obtained by means of techniques such as Control System Rapid Prototyping (RP) [5] and Hardware-In-the-Loop (HIL) simulations [1], [6], together with Automatic Program Building (APB), in order to validate the developed algorithms and systems using real time laboratory tests instead of real world tests. These techniques have been used in the PRORA-UAV Program, with particular reference to development of advanced guidance and control systems, starting from design and finishing with flight demonstration.These kinds of techniques (compliant with software development V-Cycle approach) and tools allow the definition of a design methodology in which all the development phases can be seen as part of an iterating design procedure.This paper describes the laboratory setup named On Ground validation Test Rig carried out by CIRA in the framework of the TECVOL project and reports how the described approach has been successfully adopted to develop and validate the GNC Software with particular reference to Autonomous Mid-Air Flight and Autonomous landing features.

As far as paper structure is concerned, in section II, the TECVOL project context and the autonomous mid-air flight and landing system for which we used the On Ground Validation Test Rig here proposed. In the sections III and IV, then, we will describe respectively the approach we used for the GNC design and test and the proposed On Ground Validation Test Rig. In the section V, finally, we will show the procedure used for the GNC software validation by means of the On Ground Validation Test Rig and some results of this validation stage.

E. De Lellis, V. Di Vito, L. Garbarino, C. Lai and F. Corraro are with the Italian Aerospace Research Center, CIRA, via Maiorise snc, 81043 Capua (CE), Italy (corresponding author is E. De Lellis, phone: +39-0823-623581; fax: +39-0823-623521; e-mail: e.delellis@cira.it).

A. *TECVOL framework*

Several research activities have been developed in recent years in order to increase the autonomy features in UAVs [7], in order to expand the flight envelope [8] and to improve security levels of modern aircrafts, both manned and unmanned. In particular, a significant research effort has been devoted to the achievement of high automation in the landing phase, so as to allow the landing of an aircraft without human intervention, also in presence of environmental disturbances or subsystems failures.In the framework of the national-founded project TECVOL (technologies for the autonomous flight), which continues and extends the previous CIRA project ATOL (Automatic Take-Off and Landing), successfully completed in 2004 [9], CIRA (Italian Aerospace Research Centre) developed a complete autonomous mid-air flight, collision avoidance and landing system for fixed wing aircrafts.In the ATOL project, CIRA developed the algorithms for the fixed path autonomous landing and successfully demonstrated their effectiveness by means of several in-flight experimentations, based on the use of a small scale fixed wing UAV. These algorithms still had some limitations, such as the ability to perform the autolanding manoeuvre only starting from a limited 3D region (fixed path autolanding), the use of GPS in RTK mode, the trajectory generation without considering the vehicle dynamic constraints (their satisfaction was demanded to the tracking algorithms) and the use of only basic recovery modes.The TECVOL project, therefore, aims to complete and extend the ATOL results, fully overcoming all the above mentioned limitations. This has been obtained in the TECVOL project by developing an autonomous mid-air flight system able to do 3D waypoint following and an autonomous landing algorithm able to overcome the limitations of the autolanding system developed in the previous ATOL project.

In particular, the autonomous landing system designed in the TECVOL project is able to real time generate a trajectory compliant with the dynamic constraints acting on the vehicle, performing a fully autonomous landing of a fixed wing aircraft starting from any point of the three dimensional space and using the DGPS/AHRS technology. This algorithm has been successfully tested by means of several both real time with hardware in the loop simulations [10] and flight tests [11].

B. *Functional Context*

The application for which we developed and used the On Ground Validation Test Rig described in this paper is the TECVOL autonomous mid-air flight and landing system.The autonomous mid-air flight system is designed to allow the autonomous 3D waypoints following. To do this, the system implements two different algorithms: HYTRAJ and GEOTRAJ.HYTRAJ (HYbrid TRAJectory generation) algorithm is able to generate on line a sub-optimal trajectory in order to drive the aircraft from its actual position to the desired waypoint and to cross it with the desired velocity vector, in compliance with the initial and finale desired state and with the dynamic constraints of the aircraft. The trajectory, constituted at the most by two circular arcs and one straight line, is sub-optimal, in the sense that it is the minimum length trajectory if the vehicle moves only in the horizontal plane but not necessarily it is the minimum length trajectory in the 3D space [10].GEOTRAJ (GEOmetric TRAJectory generation) algorithm does not aim to trajectory optimization but is only based on a simple connection of the fixed 3D waypoints by means of straight lines. It is obvious that the trajectory generated is not feasible for the aircraft due in general to the presence of discontinuities near the waypoints, so the tracking algorithm will assure the trajectory smoothing, allowing the capture of waypoints by means of two different modalities, as described in the next.In order to maximize the performances of the overall autonomous mid-air flight system, these two algorithms are both implemented on the GNC system and used in different flight phases.In particular, the first one (HYTRAJ) is used in order to drive the aircraft on the first waypoint, then, in order to follow next waypoints, the second one (GEOTRAJ) is used. Furthermore, HYTRAJ is used for trajectory recovery (i.e. the path re-entry after a deviation from the nominal trajectory due to external disturbances, collision avoidance manoeuvres or failures) and in order to reach the waypoint for the runway alignment in the autolanding manoeuvre.GEOTRAJ algorithm, as earlier noted, allows two modalities of waypoint capture (see Fig. 1):

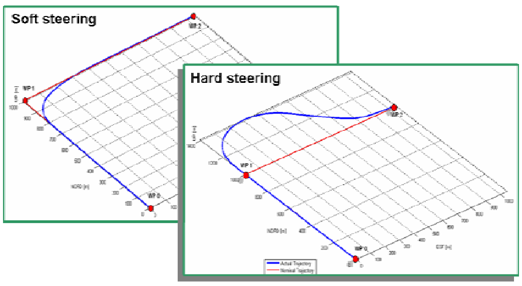

Fig. 1 Soft and hard steering trajectories

During a Soft steering the aircraft does not cross the waypoint but, when it reaches a specified control volume around the waypoint, the tracking of the next trajectory segment is started.During a hard steering – The aircraft crosses the waypoint and, then, starts the tracking of the next trajectory segment.As far as the autonomous landing system is concerned the autonomous landing process is divided into three main phases, each corresponding to a specific state of the high level mission automation logic. These main phases are called alignment, approach and touch-down (see Fig. 2) [10]-[11].

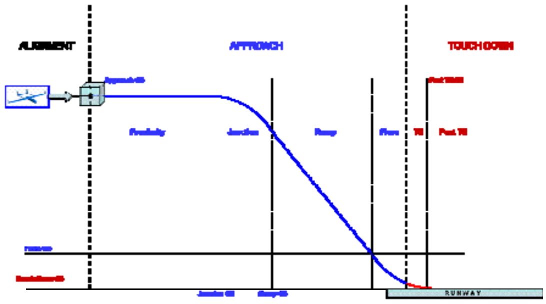

Fig. 2 Autonomous landing process conceptual breakdown

The Alignment phase is intended to move the vehicle from its generic initial state (in terms of position and velocity) to a specified state, in which the vehicle is near the runway and aligned with the centreline. The approach phase has the aim of reduce the vehicle TAS and insert it into a fixed glide path, down to a specified height above the runway, always maintaining its alignment with the centreline. The Touch Down phase, finally, is intended to provide the vehicle with the proper landing attitude. These main flight phases, described in detail in [10]-[11], will be briefly summarized in the next.The Alignment phase aims to move the vehicle from any initial condition, in terms of position and velocity, to a proper final condition. This final condition is constituted by a waypoint, specified in terms of three-dimensional position and velocity vector of the vehicle, which is located near the runway and is aligned with its centreline. In order to connect the initial position with the final waypoint, a 3D trajectory, constituted at the most by two circular arcs and one straight line, is generated on-line by using the HYTRAJ algorithm.Once completed the Alignment phase, the vehicle height above the runway is suitable for the approach phase and the aircraft is aligned with the centreline. This is assured by the proper setting of the final Alignment waypoint but, considering the presence of possible atmospheric disturbances, it is advisable to formulate the switch condition from the Alignment to the approach in terms of a three-dimensional window to be crossed by the vehicle, with a track angle limited inside a specified range. If the vehicle, at the end of the Alignment, is inside the specified 3D window and his track angle is inside the fixed range, the approach phase is initiated, otherwise the high level mission automation logic activates an appropriate recovery mode.The approach phase is divided into four segments: Proximity, Ramp, Junction and Flare. These segments, each corresponding to a specified state, are managed by a low level phase automation logic.The Proximity segment aims to smoothly reduce the aircraft TAS from the value suitable for the previous Alignment phase to a proper level for the descent towards the runway. When the vehicle arrives at a specified longitudinal distance from the runway threshold, the low level phase automation logic activates the Junction segment. This segment aims to smoothly connect the horizontal straight line reference of the Proximity segment with the glide slope reference for the next Ramp segment. Once terminated the Junction segment, the Ramp segment is activated. This segment aims to move the vehicle down to the runway, following a glide slope reference. When the height above the runway reaches a specified threshold, the low level phase automation logic passes to the Flare segment. This segment aims to reduce the vertical speed of the vehicle to a value suitable for the touch down and to increase the pitch attitude.When the vehicle height above the runway crosses a specified threshold, the high level Mission Automation Logic passes into the Touch Down phase, which aims to guarantee the proper vehicle attitude and velocity vector at the ground contact.As the weight on wheels (WoW) signal is on, the Post Touch Down segment is activated, in which all the references are direct link property commands to elevator, ailerons, rudder, throttle and flaps.The proposed autonomous mid-air flight and landing system has meaningful safety features, consisting in the ability of manage possible failures and/or severe weather conditions. These features are not still the focus of this paper, so they are not described here (see Ref. [10]).

II. Design and test approach

C. Development requirements

In the field of aerospace industry and research, the development of automation logics and control algorithms and their integration in the avionic architecture typically requires a huge effort in HW/SW design, implementation and testing. This is mainly due to current SW engineering process which foresees a tight monitoring of the SW development process for final product qualification. Moreover, a huge amount of validation tests have to be performed to obtain the final product acceptance for flight execution. For all these reasons the main GNC development requirements can be identified as a) reliable development and validation process employment and b) development time and costs reduction achievement.

D. Adopted solution

The achievement of the previous objectives may be too stringent or very time-consuming if the design process is approached using a traditional development cycle. Actually this kind of approach allows validation and testing only during the final stages of the development process. As a matter of fact if a design issue is detected during this phase, a revision of the project may be required, resulting in additional development time and additional costs.Moreover, for flight demonstrators some development requirements can be pointed out which mainly address cost limitation, short development time schedules and HW/SW flexibility in performing different missions.The above additional requirements are usually addressed by maximizing use of COTS devices for the HW avionic equipment. Furthermore, for the SW products, recently it has become widely acknowledged that techniques such as *Control System Rapid Prototyping* (RP) and *Hardware in the Loop* (HIL) simulations together with *Automatic Code Building* (APB) tools are very successful in reducing *time to market* for each development phase from requirements definition to system implementation [12].These kinds of techniques and tools allow the definition of a development methodology in which all the phases can be seen as part of an iterating design procedure. This methodology, commonly referred to as the *V-Cycle approach*, makes possible an easier interaction and a better integration of the different development cycle phases.

E. V-Cycle development approach

The development phases have to be performed using a top-down process to obtain the final product. A concept-oriented prototyping can be done to clear the requirements and to improve the customer-contractor cooperation (Fig. 3).

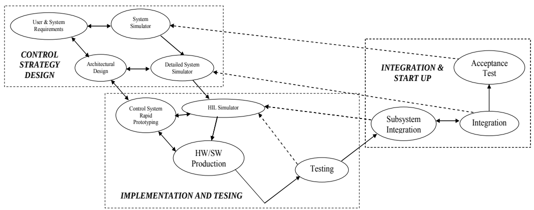

Fig. 3 V Cycle

Actually the whole design process can be divided into three main phases:

Control Strategy Design

During this phase, system and user requirements are defined, system architecture is delineated and the design of the control system is carried out through the use of simulation models (developed in *Matlab/Simulink/Stateflow* environment). Each subsystem is validated through robustness and performance off-line analysis.

Implementation and Testing

The developed control system is imported to an environment that allows the APB for a specific target machine. This approach has two main advantages:

- automation logics and control algorithms can be developed using a high level programming language;
- debugging can be easily done and during preliminary simulations while defining the control strategy and during validation of the control system using HIL simulations.

During this phase the high level language written code is integrated with C/C++ hand written code and downloaded to the target machine, that manages the resultant application according its micro-kernel's primitives.During this phase, Hardware in the Loop simulations are performed.HIL simulations allow validation and testing of the control system which can interact with both the simulated environment and the real instrumentation, i.e. feedback sensors, real Human Machine Interfaces, Airborne Virtual Cockpits, Ground Control Stations.Actually an interesting aspect of this technique is the capability to monitor and/or to modify (using SW tools) the system parameters and control strategy. In this way the validation process and the control system fine tuning becomes easy and immediate.

Integration & Startup

This is the final development phase: the GNC HW equipment is going to be integrated and GNC SW is going to be targeted and deployed in the host flight control computer, the GNC HW/SW equipment is going to be integrated in the aircraft and the system accepted after successful acceptance test session.

This development cycle has remarkable advantages especially on the quality of the final product, including:

- close correlation between control system specifications, SW implementation and related documentation;
- reduction of the code generation time;
- “strong” control over implementation and/or specification errors.

III. On Ground Validation Test Rig Description

The TECVOL experimental set-up, named On Ground Validation Test Rig, consists of both the on board and ground segments. The architecture of these segments, as it will be during the in-flight testing, is first described in the next, to explain how the laboratory validation test-rig is built starting by the real-set-up. The proposed architecture solution is sufficiently open and flexible to allow any update that may improve the development of the system.The critical components of the set-up are Commercial-Off-The-Shelf (COTS) elements, already selected and validated successfully on the platform, named FSSD (Flight Small Scale Demonstrator), used for the in-flight demonstrations in the framework of the project ATOL [9].A high level functional description of both the on board and ground segments is shown in Fig. 4.

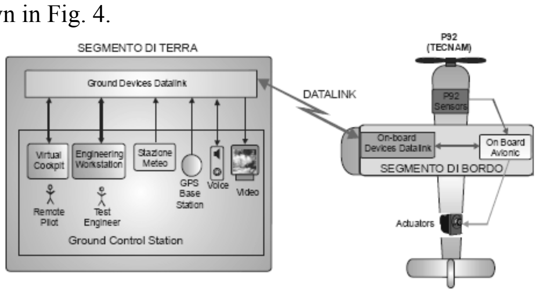

Fig. 4 High level system architecture

The main peculiarity of the proposed laboratory set-up is that we enclosed in the real time with hardware in the loop simulation also the human-machine interfaces, in addition to the aircraft and external world simulator and the FCC. In this way, the On Ground Validation Test Rig is able to perform a complete simulation of the real in-flight mission, including the human factor too.

F. *On board segment architecture*

The high-level on board segment architecture for the experimental platform, named FLARE (Flying Laboratory for Aeronautical Research), used in the framework of the project TECVOL is shown in Fig. 5.

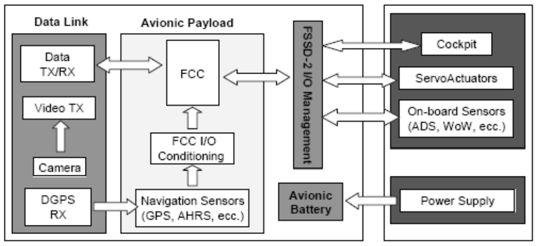

Fig. 5 On board segment architecture

The avionic architecture is based on the interconnection of the elements here listed:

- Flight Control Computer,
- GPS1, configured in DGPS mode,
- GPS2, configured in RTK mode,
- laser-altimeter,
- radar-altimeter,
- Air Data Computer,
- Attitude and Heading Reference System,
- alpha and beta sensors,
- surface position sensors,
- actuators with the own internal position sensors,
- downlink radio-modem,
- uplink radio-modem,
- GPS differential correction radio-modem,
- GPS1 avionic antenna,
- GPS2 avionic antenna.

On board are installed two GPS, configured in different ways to have a meter comparison between the aircraft position and velocity obtained by the sensors fusion algorithm implemented in the Flight Control Computer and the ones obtained by the GPS configured in RTK. In fact, the GPS radio-modem output is connected to both the GPS, in such a way as each sensor receives and selects the RTCM messages required by the RTK and DGPS algorithms.

G. *Ground segment architecture*

The ground segment architecture is described in Fig. 6.

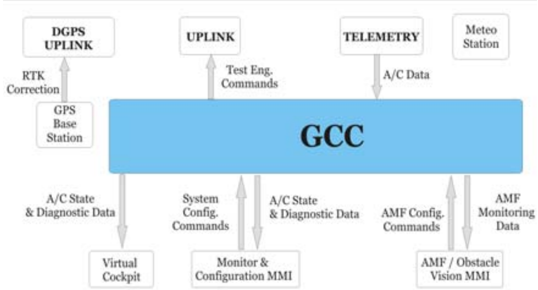

Fig. 6 Ground segment architecture

This architecture is based on the interconnection of the elements listed in the next:

- Ground Control Computer,
- downlink radio-modem,
- uplink radio-modem,
- Engineering Workstation computer,
- Virtual Cockpit Computer,
- Autonomous Mid-Air Flight Management Computer,
- GPS base station,
- GPS differential correction radio-modem.

The Ground Control Computer is based on PC104 form-factor and is the core of the whole ground segment. In fact, it is connected by an Ethernet field bus with all the computers in the ground segment and by dedicated point-to-point RS232 connection with the uplink and downlink radio-modem.Also for the ground control computer have been chosen an hard real time operating system.

H. *Laboratory set-up architecture*

Once designed the real experimental set-up, it is necessary to build a laboratory set-up that allows the testing and validation of the algorithms involved in the most critical phases of planned flight test. The critical elements identified which must be present in the laboratory validation set-up are all the ground segment and the Flight Control Computer.A complete validation test of these elements could be done only implementing a flight simulator, which allows to achieve the mission flight designed for the real set up. The CIRA experimental flying platform is a manned vehicle so the procedure used by the pilot, that will assume the function of safety pilot, in a real mission can be summarized as follows:

- the pilot activates the autonomous flight switching the “test request” button installed on the aircraft;
- if the conditions required for the beginning of the test are satisfied, the pilot receives a visual feedback on the actuator hired led installed on his cockpit;
- if the “test request” command is activated but there aren’t the conditions to start or to continue the mission, a critical alarm led is activated on the pilot’s cockpit;
- if the mission is terminated successfully, an end-test led will be hired on the pilot’s cockpit.

To simulate the real mission by means of the laboratory set-up, the most important requirement is that the laboratory test-rig has to be able to acquire the pilot direct link commands. Furthermore, the laboratory test rig has also to replicate the visual led present on the real pilot cockpit.

These aspects of the management of real mission must necessarily be implemented even in the laboratory set-up for all phases of flight mission to be accomplished. The laboratory set-up functional architecture designed and based on the considerations previously made is shown in Fig. 7.

The elements included in the laboratory set-up are:

- Flight Control Computer,
- Ground Segment,
- Aircraft and Sensors simulator,
- Pilot Cockpit and Interceptor Commands Emulator.

As shown in Fig. 7, the aircraft and sensors simulator is interconnected with both the Flight and Ground Control Computers. This choice has made because in the laboratory set-up the Ground Control Computer manages also the communications with the pilot's cockpit simulation computer. This connection is not present in the real experimental set-up, but it is necessary to simulate the direct connection between the pilot’s cockpit and the aircraft.For the acquisition of pilot direct link commands, the management of the laboratory pilot real cockpit and for the data communications management between aircraft simulator and ground segment, we use the same hardware platform. This is not a limitation of the proposed On Ground Validation Test Rig, because the software module designed for the pilot commands acquisition and laboratory real cockpit management does not have any link with the software module designed to the data management between the ground segment and the on board segment.

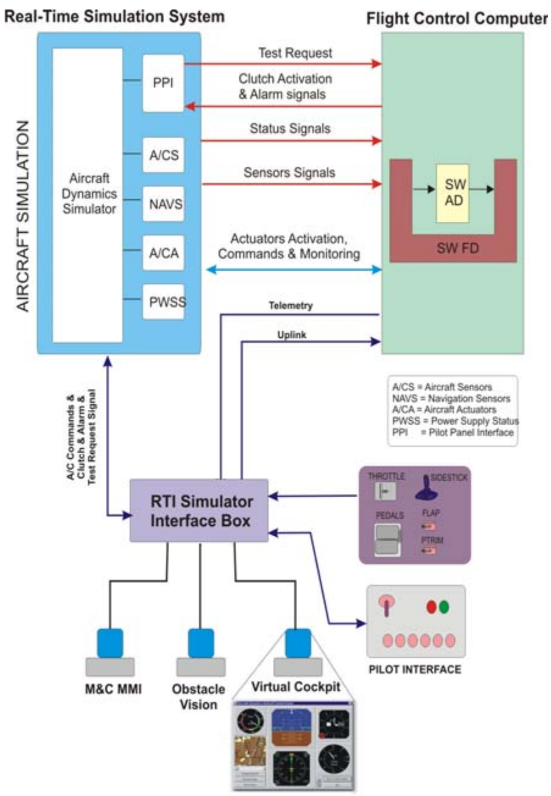

Fig. 7 Laboratory set-up architecture

The aim of the laboratory set-up is to test the software implemented on the Flight Control Computer and the ground segment software needed for the mission flight management. Achieving this goal is done correctly simulating all sensors on board. The software architecture of the aircraft and sensors simulator is composed by the modules here listed:

- six degrees of freedom (6dof) aircraft model module,
- sensors simulation module,
- external interface sensors simulation module,
- actuators simulation module,
- external weather conditions simulation module,

- pilot's cockpit management module.

The 6dof aircraft model module is the core of the whole simulation software. The sensors and external interface sensors simulation modules are based on the COTS elements installed on the experimental set-up. The actuators simulation module implements the open loop model of each actuator. The external weather condition is necessary to simulate wind gust, shear and turbulence in all flight phases. The Pilot's cockpit management, finally, is a software module which acquires the laboratory pilot commands trough a RS232 serial communication direct link between the 6dof aircraft model of the vehicle and the pilot commands acquisition software implemented on a PC104.

I. *Laboratory mission simulation procedure*

Once briefly described the laboratory set-up architecture, it shall be described the procedure for the laboratory simulation of a flight mission.The real time hardware in the loop simulation starts with the aircraft in a trimmed state and continues based on the procedure described in the next.

- The test engineer sends from the Engineering Workstation the command to activate the flight data recorder (FDR) and immediately, if the command is confirmed, on the workstation the FDR_ON led is activated;
- The laboratory pilot, using the joystick that replicates the on board pilot commands, performs the manual manoeuvre to bring the aircraft in the flight condition provided for the test. Throughout this phase of flight, all the variables of interest for the mission are tracked through the virtual cockpit and engineering workstation.
- In this first phase, during the pilot manual control of the aircraft, the test engineer selects by means of the engineering workstation the manoeuvre to be activated (AMF, AL or AMF+AL). The system transmits uplink directly to the on board computer (FCC), which receives the command and communicates to the engineering station that the command has been received correctly.
- The test engineer asks the pilot, in the laboratory verbally while in the case of the experimental set-up via radio, to activate the "test request" command for switching to autonomous flight. At this point, the aircraft simulator software receives the "test request" and the commands to surfaces in input to the aircraft model switch from the pilot ones to those generated by the flight control computer.
- If the on board flight control computer detects that all the necessary and sufficient conditions for the autonomous accomplishment of the flight are satisfied, it enables pilot's cockpit led, communicating that the computer took control of the aircraft. At the same time, this information is transmitted by telemetry to the engineering workstation.
- The aircraft carries out the selected mission and, once this mission has been completed, the FCC activates the "end test" command. The pilot receives the "end test" information in a visual way through a proper led on his cockpit while the control station receives via telemetry the information that on board "end test" led has been activated.
- Once received the information that the mission is ended, the pilot disables the "test request" switch and takes the manual control of the aircraft.
- The test engineer stops the simulation and begins the download of the data stored in the flight data recorder for the post flight analysis.

The description just made refers to the case of a mission without failures. Of course, often failures affecting for instance sensors, actuators or datalink loss happen during a mission. This means that it is necessary to test both the on-board software and the ground control station even in presence of failures, in order to verify that the design choices initially made are correct or modifications are needed, based on the results obtained in the laboratory simulation.The TECVOL On Ground Validation Test Rig allows at any time of the mission, both in manual and in autonomous flight modes, the simulation of different failures. This aims to verify logical diagnostic on the various elements of the avionics system and the behaviour of the flight management system in response to such events. If the failure does not compromise the success of the mission, the system does not enable alarm led always placed in the cockpit of the pilot, while if the failure is critical for the mission prosecution, the mission automation logic activates a safety status, enable the alarm led suggesting to the pilot to take the control of the aircraft.

IV.GNC Autoland and AMF Software Module Validation by means the On Ground Validation Test Rig

The GNC autonomous mid-air flight and landing system has been validated by means of several real time with hardware in the loop simulations [10] and by means of many real in-flight tests [11].The real time GNC SW testing phase has been performed by using the On Ground Validation Test Rig described in the previous section. During the TECVOL project development it has been performed a relevant amount of real time tests of both AMF and AL GNC systems, including several failure cases. In these tests, all the run time constraints have been satisfied and the GNC system has demonstrated its effectiveness.Of course, in this paper only few tests can be reported, so in the next we will describe only three real-time with hardware in the loop simulations, in order to emphasize the flexibility of the above proposed On Ground Validation Test Rig and its usefulness in testing different GNC algorithms in very different operational conditions. The results of these tests are not described and discussed in particular, because the focus of this paper is not the GNC algorithms performances analysis.With reference to the flexibility of the On Ground Validation Test Rig, it must be noticed that this laboratory experimental set-up is able to allow the real time with hardware in the loop simulation of several different algorithms implemented in the GNC system, such as the ones mentioned in this paper (AMF and AL) and also other algorithms at present in the development phase (for instance the Autonomous Collision Avoidance algorithm, whose development is currently in the off-line testing phase).

Regarding the usefulness of the On Ground Validation Test Rig developed by CIRA in the framework of the project TECVOL, it must be emphasized that this real time environment is able to allow the simulation of several operating conditions for the aircraft, including the consideration of environmental disturbances (wind gust, wind shear and turbulence) and the simulation of failures regarding the flying platform and its on board hardware systems.

The wind disturbances can be tuned by the operator, which can choose their magnitude, direction, height of disturbances start and stop and so on.The failures simulation also can be customized by the operator, which is able to select among several types of failures and can choose if simulate only one failure or multiple failures. The time of failure start and its duration (or, equivalently, the heights of failure start and end) are also selectable by the operator of the On Ground Validation Test Rig.Some of these features of the CIRA On Ground Validation Test Rig, which make this platform very flexible and useful in the real time experimental validation of the GNC system, are showed in the next. In particular, we consider three real time simulation test cases, in which we include always the presence of both atmospheric disturbances and sensors noise and errors.

The examined cases are:

- Case A: autonomous landing, without failures, with persistent wind gust, nose oriented during approach and touch down phases.
- Case B: autonomous landing, with GPS link failure during Flare segment and persistent wind gust, laterally oriented in the approach phase.
- Case C: autonomous mid-air flight, with multiple failures (GPS link and ADS failures) during the waypoint following phase and persistent wind gust.

Case A – This case refers to an autonomous landing manoeuvre, without failures during the flight, in presence of a persistent wind gust which is nose oriented during approach and touch-down phases. The system is commanded to perform an autonomous landing manoeuvre starting from an arbitrary position and the simulation is stopped after the contact of the rear landing gear. An overview of the test conditions, including initial position and speed of the vehicle, waypoint to be reached in the Alignment phase, environmental conditions and so on, is reported in Table 1.

The procedure used for this simulation by means of the On Ground Validation Test Rig can be briefly described as:

- FDR activation;
- setting of the environmental disturbances;
- selection of the experiment to be executed (AL);
- simulation starting.

Once the autolanding manoeuvre has been performed, the simulation is stopped by means of the proper interface and the data are downloaded from the FDR and converted in a suitable format in order to be analyzed using Matlab.

TABLE I
TEST CONDITIONS FOR THE CASE A

Case A test conditions		
Runway	Orientation (NEU reference) [deg]	-120
Vehicle initial position and inertial speed	$x_{0\ RW}$ [m]	-600
	$y_{0\ RW}$ [m]	2000
	$z_{0\ RW}$ [m]	300
	$V_{0\ inertial}$ [m/s]	40
	χ_0 (NEU reference) [deg]	0
	γ_0 [deg]	0
Atmospheric disturbances	Wind gust magnitude [m/s]	5
	Wind gust direction (NEU reference) [deg]	60
	Turbulence	Yes
Alignment WP	x_{WP} [m]	-1900
	y_{WP} [m]	0
	z_{WP} [m]	75
	χ_{WP} (NEU reference) [deg]	-120
	γ_{WP} [deg]	0

The results of this real time application are reported in Table 2 (notice that the nominal touch down point is $x_{RW\_TD\_Nom}$= 75 m, $y_{RW\_TD\_Nom}$= 0 m), while from Fig. 8 to Fig. the 3D spatial representation of the autonomous landing manoeuvre and the time histories of a limited subset (height above runway, vertical speed, TAS tracking and inertial speed and pitch angle) of the interesting quantities are shown.

TABLE II
TOUCH DOWN PERFORMANCES FOR THE CASE A

Case A touch down performances	
Δx_{RW} [m]	-24.1
Δy_{RW} [m]	-2.5
TAS [m/s]	24.8
$V_{inertial}$ [m/s]	19.8
V_y [m/s]	-0.1
V_z [m/s]	-0.4
φ [deg]	0.5
θ [deg]	5.3
ψ [deg]	-119.8
α [deg]	6.2
β [deg]	-0.2
n_z	1.3

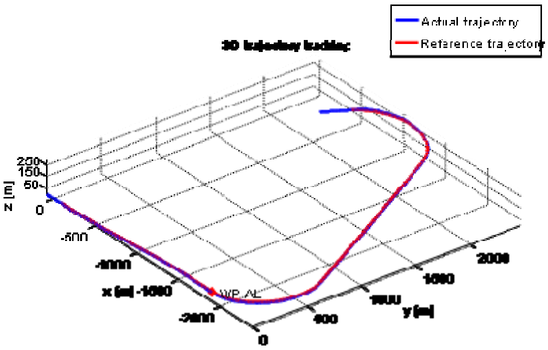

Fig. 8 Case A: 3D nominal and actual trajectories

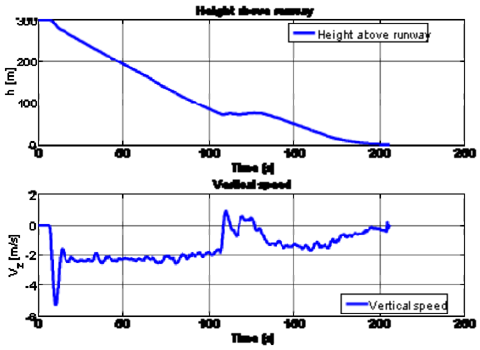

Fig. 9 Case A: height and vertical speed versus time

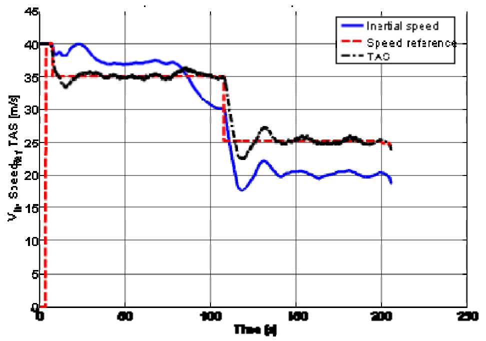

Fig. 10 Case A: TAS tracking and inertial speed versus time

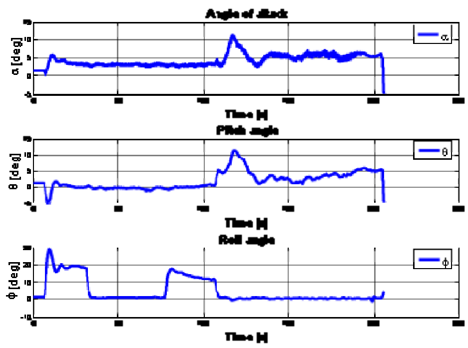

Fig. 11 Case A: α, θ and φ versus time

Case B – This case refers to an autonomous landing manoeuvre, in which a GPS link failure occurs during the Flare segment of the approach phase, in presence of a persistent wind gust which is laterally oriented in the approach phase. The system is commanded to perform an autonomous landing manoeuvre starting from an arbitrary position and the simulation is stopped when the aircraft completes the landing manoeuvre, once finished the failure. An overview of the test conditions, including failure time allocation, initial position and speed of the vehicle, waypoint to be reached in the Alignment phase, environmental conditions and so on are reported in Table 3.

The procedure used for this simulation by means of the On Ground Validation Test Rig can be briefly described as:

- FDR activation;
- setting of the environmental disturbances;
- setting of the failure to be simulated (GPS Link);
- selection of the experiment to be executed (AL);
- simulation starting.

Once the autolanding manoeuvre has been performed, the simulation is stopped by means of the proper interface and the data are downloaded from the FDR and converted in a suitable format in order to be analyzed using Matlab.

TABLE III
TEST CONDITIONS FOR THE CASE B

Case B test conditions		
Failure configuration	GPS_Link_Fail initial time [s]	130
	GPS_Link_Fail final time [s]	140
Runway	Orientation (NEU reference) [deg]	-120
Vehicle initial position and inertial speed	$x_{0\ RW}$ [m]	-1000
	$y_{0\ RW}$ [m]	-2000
	$z_{0\ RW}$ [m]	100
	$V_{0\ inertial}$ [m/s]	35
	χ_0 (NEU reference) [deg]	0
	γ_0 [deg]	0
Atmospheric disturbances	Wind gust magnitude [m/s]	4
	Wind gust direction (NEU reference) [deg]	-30
	Turbulence	Yes
Alignment WP	x_{WP} [m]	-1900
	y_{WP} [m]	0
	z_{WP} [m]	75
	χ_{WP} (NEU reference) [deg]	-120
	γ_{WP} [deg]	0

The results of this real time application are reported in Table 4 (notice that the nominal touch down point is $x_{RW\_TD\_Nom}$= 75 m, $y_{RW\_TD\_Nom}$= 0 m), while the 3D spatial representation of the autonomous landing manoeuvre and the time histories of a small subset (failure signal, height above runway, vertical speed, TAS tracking and inertial speed, angle of attack, pitch angle, roll angle) of the interesting quantities are shown from Fig. 12 to Fig. 16.From the analysis of these figures and in particular from Fig. 13 and Fig. 14 it results that when the failure occurs the mission automation logic activates a proper recovery mode in order to drive up the aircraft, then, once the failure ends, the mission automation logic activates again the autonomous landing manoeuvre.

TABLE IV
TOUCH DOWN PERFORMANCES FOR THE CASE B

Case B touch down performances	
Δx_{RW} [m]	11
Δy_{RW} [m]	0.2
TAS [m/s]	24.5
$V_{inertial}$ [m/s]	24.2
V_y [m/s]	0.2
V_z [m/s]	-0.3
φ [deg]	0.1
θ [deg]	5.9
ψ [deg]	-122.2
α [deg]	6.7
β [deg]	-6.6
n_z	1.3

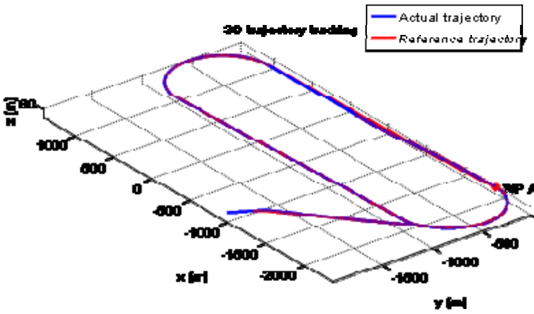

Fig. 12 Case B: 3D nominal and actual trajectories

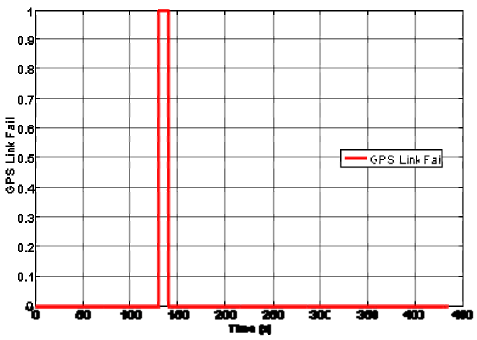

Fig. 13 Case B: failure signal versus time

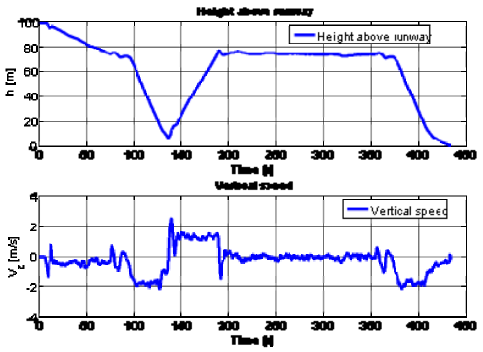

Fig. 14 Case B: height and vertical speed versus time

Case C – This case refers to an autonomous mid-air flight with 3D waypoints following manoeuvre, in which first a GPS failure (in particular a GPS Link failure) occurs during the waypoints following phase and then, after 10 s from the GPS failure starting, an Air Data System failure (in particular a Pressure Altitude failure) also occurs. After 30 s from the starting of the ADS failure, both the failures are stopped and the system returns in the normal mode.

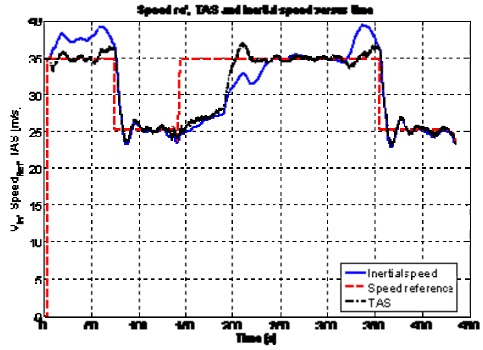

Fig. 15 Case B: TAS tracking and inertial speed versus time

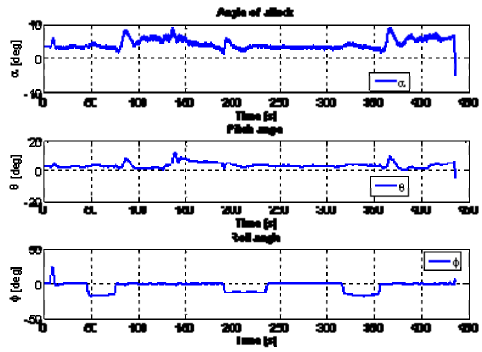
Fig. 16 Case B: α, θ and φ versus time

The waypoints following manoeuvre is commanded starting from an arbitrary position, the real time simulation includes the presence of a persistent wind gust and is stopped when the aircraft completes the waypoints following manoeuvre, once finished the failures. An overview of the test conditions is reported in Table 5.The procedure used for this simulation by means of the On Ground Validation Test Rig can be briefly described as:

- FDR activation;
- setting of the environmental disturbances;
- setting of the failures to be simulated (GPS Link and PALT Rate);
- selection of the waypoint list to be followed;
- selection of the experiment to be executed (AMF);
- simulation starting.

Once the waypoint following manoeuvre has been performed, the simulation is stopped by means of the proper interface and the data are downloaded from the FDR and converted in a suitable format in order to be analyzed using Matlab.

TABLE V
. TEST CONDITIONS FOR THE CASE C

Case C test conditions		
Failure configuration	GPS_Link_Fail initial time [s]	50
	GPS_Link_Fail final time [s]	90
	Pressure Altitude Fail initial time [s]	60
	Pressure Altitude Fail final time [s]	90
Atmospheric disturbances	Wind gust magnitude [m/s]	2
	Wind gust direction (NEU reference) [deg]	-120
	Turbulence	Yes

With reference to the results of this real time application, the 2D spatial representation of the autonomous waypoints following manoeuvre and the time histories of height tracking and failure signals are shown from Fig. 17 to Fig. 19.From the analysis of these figures, it results that during the failures the mission automation logic activates a proper recovery mode in order to drive the aircraft with a proper attitude, then, once the failures end, the mission automation logic activates again the autonomous mid-air flight phase in order to reach the appropriate path re-entry waypoint (in this case WP 3) and to continue the waypoint following manoeuvre.

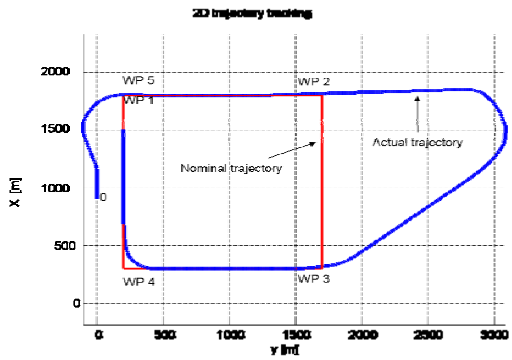

Fig. 17 Case C: 2D nominal and actual trajectories

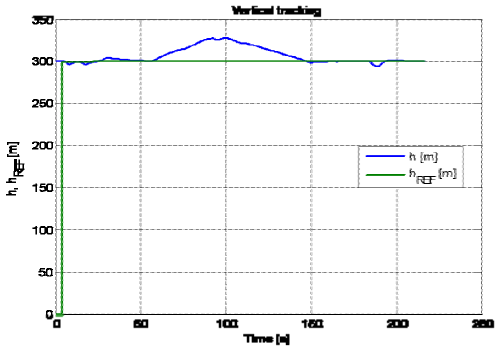

Fig. 18 Case C: height tracking versus time

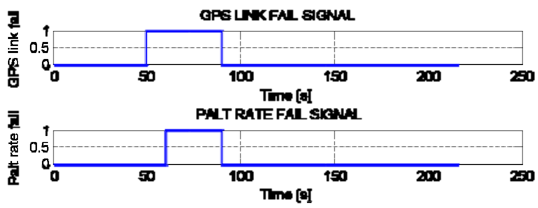

Fig. 19 Case C: failure signals versus time

From the analysis of data and graphics referred to examined cases, it results that GNC system AMF and AL algorithms perform very good, in compliance with the desired performance constraints and recovery procedures [10].The test cases here described show the flexibility and the usefulness of the On Ground Validation Test Rig here proposed in the GNC algorithms development and testing phase.

V.CONCLUSIONS

This paper described the design process and real-time validation of the autonomous mid-air flight and landing system recently developed by the Italian Aerospace Research center (CIRA) in the framework of the TECVOL project. It reported an insight about all the design phases, with particular emphasis on the successful application in the whole design process of the "V-Cycle" approach, including the real-time with hardware-in-the-loop validation of the system by means of the properly designed on ground-validation test rig.This test rig, considered of very importance in order to allow the implementation of the "V-Cycle" approach, has been also described in details in the paper. Particular emphasis has been devoted to the relevant peculiarity of the proposed on-ground validation test rig, which includes in the real-time with hardware-in-the-loop simulation also the human-machine interfaces, in addition to the aircraft and external world simulator and Flight Control Computer (FCC). In this way, the laboratory test rig allowed to perform a complete simulation of the real in-flight mission, including the human factor too.In the paper, furthermore, some laboratory real-time with hardware in the loop simulations have been reported, showing the flexibility of the proposed test rig and its usefulness in testing different algorithms in very different operational conditions.

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