Flight Envelope Opening of a VTOL UAS

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INTRODUCTION

Beside its major activity in the development of piloted helicopters, Airbus Helicopters has been developing for a decade now VTOL UAS systems. Regarding flight testing, opening the envelop of an UAS is a complete change of paradigm: when, on a manned helicopter, the flight envelop can be opened step by step and always relies on the capability of the on board pilot to recover and to come back to a safe envelop, on a UAS, the level of automation, the complexity of the overall system, the reduced awareness due to remote control and monitoring and the site and airworthiness constraints are new challenges adding to the standard problems of flight testing a VTOL.

This paper describes the methods used to open the flight envelope of the VSR700 Unmanned Aircraft System (UAS). The VSR700 is the leading UAS program in Airbus Helicopters which enabled to grow competencies in VTOL UAS development. A focus will be made on two specific flight testing phases: the initial speed/altitude domain opening coupled with the tuning of the autopilot and the Ship-Helicopter Operating Limits (SHOL) opening.

When dealing with heavy UAS, the flight test logics can be either to minimize the development time, whatever the risks. It can also be to minimize the risk, leading to long development time. The flight test technique that was adopted is a compromise between these two strategies.

VTOL UAS / DRONIZATION OF A CERTIFIED HELICOPTER

The VSR700 [1] is a drone under development for the French Navy, based on the Cabri G2 helicopter. It is a 700kg-class drone, heavier than most native drones. The main mission of the VSR700 is to perform maritime surveillance with an Electro-Optical Sensor and a Radar from a FREMM Frigate, where the VSR700 drone will be parked in the hangar alongside with a NH90 helicopter.

This system consists of an Unmanned Aerial Vehicle (UAV), a ground control station (GCS), and a datalink (DL). The UAV is based on a Cabri G2 helicopter modified by:

- Reshaping the cabin to better accommodate the internal system and the external payload
- Installing a dual duplex full authority Flight Control System fed by a full set of sensors (including inertial, position and ground detection sensors)
- Installing a new Jet-A1/Avcat compatible dual channel FADEC engine
- Installing a digital vehicle management system

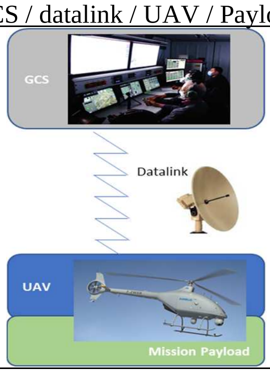
UAS: GCS / datalink / UAV / Payload	Cabri G2 Vs VSR700
	

Figure 1 : UAS definition. Cabri G2 compared to VSR700

The piloting modes are those of a standard drone (navigation, return to base, geofencing) plus some specific modes to support specific tasks like automatic ship deck take-off and landing [4]

The level of automation is high which adds a complexity in flight envelop opening and some specific piloting modes / features dedicated to development flight tests have been developed as will be detailed later.

Figure 2: VSR700 during the flight test campaign on FREMM Provence

FLIGHT ENVELOP OPENING OF MANNED ROTORCRAFT

The flight envelope of an aircraft refers to the environmental and rotorcraft parameters in which the rotorcraft will operate. The altitude and temperature range, the maximum rotorcraft weight and its center or gravity (CG) extremes, maximum wind, etc. In a manned rotorcraft, the flight envelope is opened during the initial flights of a new prototype, but also when the envelope of an existing model is extended because of design changes (e.g. new engines, new rotor…) [3].

Before opening the flight envelope, all critical parameters are identified. This usually includes dynamic and static flight loads, power limits, vibration levels, control margins, temperatures. From this, a list of parameters that needs to be closely monitored in telemetry and in flight is identified.

The incremental approach is based on three principles:

- Whatever the linearity of the phenomena, small increments of the parameters lead to linear evolution of the limits (e.g. flights with wind from different directions). This is the gradient method.
- Once the domain is opened, it is presumed as safe. A small increment of the parameter (e.g. airspeed) allows an easy return to the “safe” domain that was already opened. It supposes that the phenomena, in the safe domain, are damped enough.
- As the test pilot has full authority in terms of command travel, command speed, any upset position can be recovered. The implicit prerequisite behind the combination of command travel, command speed (what is usually called “command activity”), is the pilot’s workload : this can be one criteria to stop the envelope opening. This prerequisite is very important and goes beyond the sole flight controls, but also to every crew action on the helicopter configuration [3]

During the flight, a close follow-up of safety parameters is performed:

- On board, using FTI
- On ground, using telemetry

But there is more than this! An increase of a noise or vibrations can be a hint that something is changing – even if this change is below the alert threshold. But sometimes small changes can quickly "explode" to a serious phenomenon. The overall behavior of the helicopter, as well as the pilot workload can also provide good clues to stop the test point. The experience of the crew, inconsiously compares the actual response of the helicopter to the known one. This is very hard to translate into an automated monitoring algorithm.

FLIGHT ENVELOPE OPENING OF AN UAS: A CHANGE OF PARADIGM

The UAV (Unmanned Air System) is a system of systems. The flight envelope encompasses the usual flight domain of the UAV, but also the datalinks, and the functional domain of the ground segment. Such aspects have been widely studied for small drones [4] but less shared for heavy VTOL submitted to high airworthiness constraints like the UAVS developed by Airbus Helicopters.

At first sight, one might think that opening the flight domain of a "dronized" but already certified rotorcraft is a walk in the park. However, the VSR700flight test campaigns showed that :

- Some flight envelope demonstration can be easily performed by a pilot in command. However, the same demonstration can be very difficult to perform with an UAS. Flight control laws only react to minimize error between a target and a current parameter, whereas pilot can decide to adapt the way he flies according to the circumstances (eg : turbulence, eigen characteristics of the helicopter). This difficulty applies as well to piloted rotorcrafts if piloted actions are automated [5]
- The incremental approach (in weight, NR, wind, turbulence, slopes) can have detrimental effects : in particular, the static limit approach (static command margin) isn't robust enough to prevent speed saturation, or latent control loss
- Whereas datalinks (DL) may be considered as mission elements on piloted helicopters, their contribution is as crucial as flight control systems on UAV. In particular, a high importance must be paid to cover the cases of partial / total loss of DL.
- Safety functions (recovery function) have to be thought to be easy to use, with full authority. This will be further detailed as well.
- Having high frequency actuators can not only couple rotor eigen modes (already problematic on manned rotorcraft), but also on structural eigen modes (above 4Hz). Particular attention was paid to this during the flight tests
- Whereas on piloted helicopters the test pilot can take controls at any time to recover, the experience shows that the whole time lag (perception, decision, action on controls, UAV reaction time) doesn't allow to always recover. On some phases, such as takeoff or landing, a decision point must be used in order to decide the UAV to continue the maneuver (with criteria to decide), or recover. These 3 last points required to adapt the flight test technique, as well as the development sequence of the flight controls. This will be developed in the dedicated paragraph.

Figure 3: Slope take-off and landings, good example of incremental approach

STATIC MARGIN : NEED FOR ADDITIONAL CRITERIA

The figure 4 shows a quartering flight where the groundspeed (bottom right) is increased from 20kts to 25kts, with initial FCS gains settings. Tail rotor command Ddn (3rd line, left), shows activity, but with good margin (70% with a full stop at 100%). As soon as the groundspeed is increased towards 25kts and stabilized, Ddn shows increased activity, with linear shapes. 5s after stabilizing the groundspeed target, the heading control is lost, with excursions (first line, left), at 150 degrees. The Ddn position is interesting: it is purely linear.

This flight test shows that, in this case (initial gains settings), the static margin is good, but the command rate is saturated: the flight controls speed is at its maximum, limiting the bandwidth. This handling quality aspect wasn't experienced with the piloted Cabri: the pilot can reach higher command speeds. This shows that, even if the method was incremental, the cues for assessing the margin are not the same as for usual piloted flight domain opening.

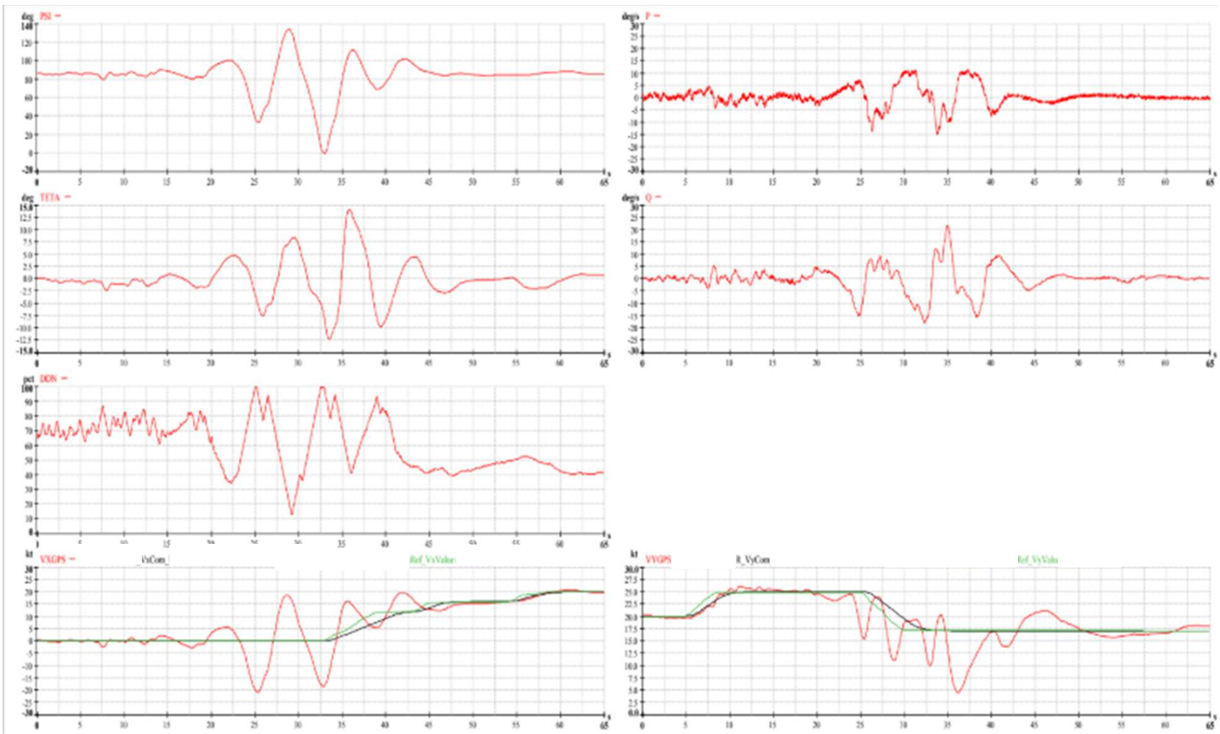


Figure 4: Example of flight envelope opening where usual criteria are not sufficient

DEGRADED SITUATIONAL AWARENESS

The situational awareness is a mental process where a person will make a decision upon perceived elements, based on his understanding and his projection. The figure 5 is based on [6].

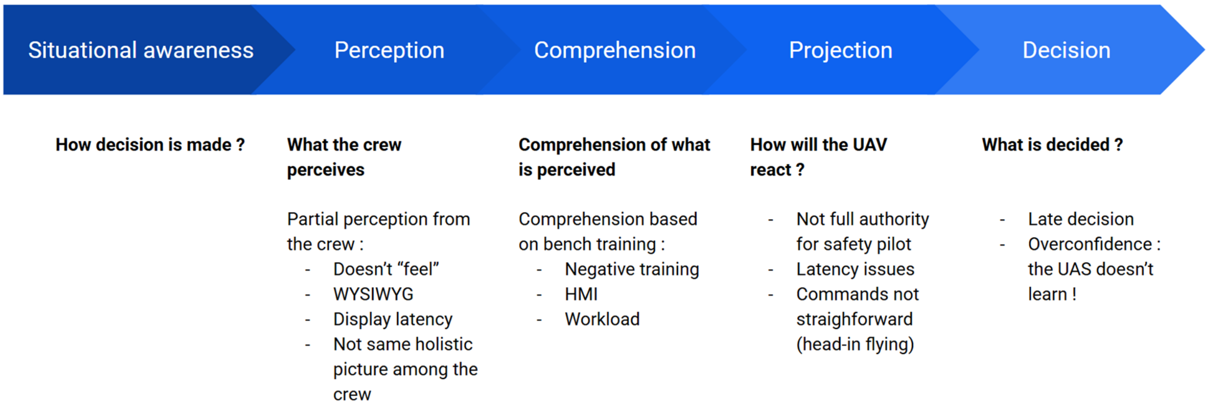


Figure 5 : Situational awareness process and UAS particularities

The **perception** of an UAS is somehow difficult: it is partial as the crew does not feel the rotorcraft (e.g.: sound, vibrations). The WYSIWYG phenomena is What You See Is What You Get, inspired from typing software where what you see typed on your computer screen, can be quite different from what you'll retrieve from the printer… All what the flight test crew perceives on ground is seen through the system under test itself: it can be bugged, show latency. Flight Test Instrumentation can help to have a critic view on the displayed information, such as basic piloting information (indicated airspeed, attitudes…), or vehicle information (engine power, flight controls mode…). On top of these difficulties, as the information to be displayed are numerous, the displays are dense and don't display the same information. The crew don't share the same holistic picture and therefore an increased information sharing is needed, which represents potentially a dense intercommunication.

The **comprehension** is what the crew understands, based on perception. As the crew relies only on displayed information, and have a partial perception, the understanding is helped by intense training on bench to get familiar with the procedures, the zones and the flight test maneuvers to be performed. However, this can be subject to negative training as modeling can be partial, non-fully representative, and lead to wrong reactions. The high workload, dense cross-crew communication can make difficult to understand in real time, get the right "big picture" of the situation. In some cases, the understanding can be different from the crew position (flight test engineer, test pilot) as they have different sources of information.

The **projection** is how the crew projects in the future, based on the understanding and the knowledge of the system itself. In some cases, the system can react not as quickly as would a piloted rotorcraft: the system itself can show neither full authority, nor full command speed authority, so the reaction of the UAV can be more sluggish which can be challenging for recovery actions near the ship deck. In some flight phases, the projection isn't easy to make, such as flying the UAV in front of the pilot, where commands are inverted (left stick will move the UAV to the pilot right). When the pilot is continuously flying the UAV, this inversion is intuitive. But when the test pilot has to take over from a full automated flight, this can be tricky.

The **decision** is the conclusion of this mental process: the crew decides what to do. In UAS activities, the decision can be difficult to make, based on the difficulties developed before. This can lead to late decision. Last, the usual mindset of the flight test crew, on manned rotorcrafts, is to begin the flight campaign cautiously, expand the domain and get used to the rotorcraft behavior; margins can be safely reduced. When dealing with an UAS, the system doesn't learn and unconsciously the crew can reduce margins, but puts safety at risk: UAS improves with software updates, not with flight hours flown.

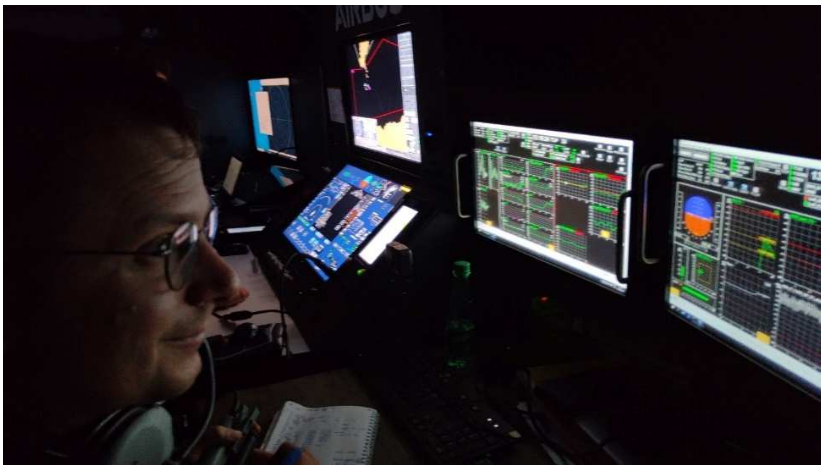


Figure 6: **Trying to board the flight test whilst watching FTI parameters**

The lessons learnt from the flight test campaigns showed that the Ground Control Station (GCS) has to be considered as a cockpit : in order to focus on parameter, figure out the airborne situation whilst looking at the FTI curves, roaming discussions, entering/exiting the GCS have to be minimized in order to avoid loss of situational awareness.

TAKE INTO ACCOUNT THAT RECOVERY ISN'T ALWAYS POSSIBLE

Based on the specific situational awareness concept in the UAS flight tests, it was identified that recovery actions were not obvious, could be late and lead to sluggish recovery trajectory. In some cases, when nearing flight domain boundaries (eg : extreme deck motion), the recovery may have detrimental effects.

In that respect, a dedicated decision height has been put in place, where a recovery (abort) is allowed above, and prohibited below. The decision criteria are based on trajectory : relative vertical speed of the UAS with regard to the deck, horizontal trajectory (accuracy of the UAV position wrt ship deck reference point).

With such a method, late recovey actions are excluded, but it also means that for such domain exploration, there is no escape once the decision height is reached at descent.

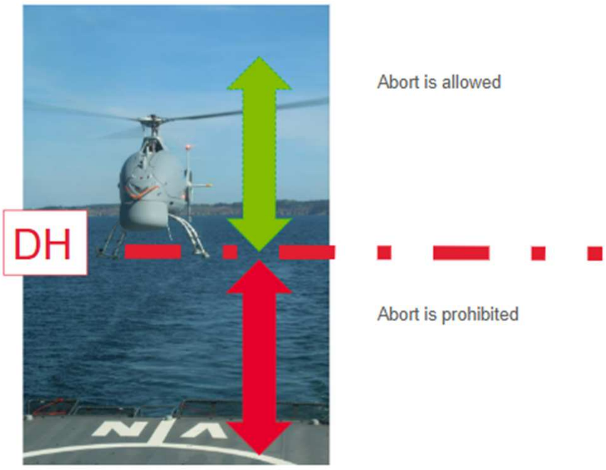


Figure 7: Dedicated decision height method

COMPLEXITY DUE TO SITE AND AIRWORTHINESS CONSTRAINTS

Whereas traditional manned rotorcraft are airworthy to fly wherever it can be useful, the flight test area for a UAV belongs to the flight conditions as it carries safety substantiation, such as emergency response plan, population density, manned/unmanned traffic proximity. This creates an additional level of complexity that has to be dealt with. In the initial flights, a “white” area, with zero people density was used. As long as the program ran, and the maturity increased, the following steps were reached :

- Use of sparsely populated area
- Use of civil airports, in cooperation with Air Traffic Control

Step	1	2	3	4
Site	white	segregated	segregated	Low density
Safety contributors	FTS	FTS + Geofencing	FTS + Geofencing	Geofencing + system V&V
Overall Maturity	Low	Medium-	Medium	High
Test Program	First tests Take-off, Landing, hovering	Speed / Altitude / Weight opening	Mission tests, performance Maturity	Ship SHOL Mission tests (elongation & payload) MuM T
Flight Test Leader	Deported GCS pilot	Main GCS pilot	Main GCS pilot	Main GCS pilot
Photo				

Figure 8: **Typical site and airwothiness constraints evolution**

Figure 9: **VSR700 flying in Aix Les Milles (LFMA) airport**

PREPARATION FOR UAV FLIGHT ENVELOP EXPANSION / DEVELOPMENT LOGIC

Simulation rigs were intensively used for 3 purposes:
- Assess the trajectories before defining the flight procedures:
  - o Return To Base (RTB) trajectory
  - o Geofencing and RTB activation behavior
- Assess the HMI and AFCS functions and perform the necessary bug fixings / improvements
- Become accustomed to handling the entire system.

As the usual senses of the crew are not used (sight, hearing, smell, touch), the crew has to mentalize the actions and the flight test sequence before the flight. In addition to a poor situational awareness, the zone dimension is usually limitative: the flight test order has to be adapted and the crew has to be highly prepared to the zone before the test campaign.

In order to ease initial testing of the technology bricks of the UAV, on top of integration bench, an Optionally Piloted Vehicle (OPV) was also used, with a safety pilot onboard. This permitted the easy development of flight control laws, especially automatic take-off and landing laws for land and shipboard landings. It allowed obtaining a good system maturity before performing the remotely piloted UAS flights. The OPV mode was also used to train the crew to remotely fly the UAV and to investigate the impact of system failures.

The OPV was used for the first step of this program, and was also used to test the new functions that would be implemented in the UAS.

To prepare for a new test campaign, the OPV has been used for three purposes:
- Assess the behavior of the UAS following given failures
- Assess the behavior and the consistency of the trajectories (yaw rate in hover, RTB trajectory)
- Continue the training of the flight test crew

The development of the FCS relied on three testing means:
- Simulation
- Prototypes with safety pilot on-board (Optionally Piloted Vehicle)
- Prototypes without safety pilot on board

Simulation	*OPV*	*Unmanned aircraft*

Figure 10: Test strategy for flight controls

The simulation enables to validate and verify the flight modes. Prototypes with safety pilot on board (system disconnected in case of failure and pilot recovering the piloting) enables to iterate quickly on specific modes like Automatic Takeoff and Landing (ATOL) and with a reduced level of Verification and Validation (V&V). Unmanned prototypes enable to finally test functions in real environment.

For flight in unmanned configuration, a stepwise approach was adopted. Risk level is a combination between severity and occurrence. When confidence is poor, occurrence of accident can be high, but risk level can be acceptable providing minimization of severity. This is typically achieved by flying in white area. Flying above low density area increases the severity (consequences for third parties), and therefore requires a better confidence in the design. The flight test area (white area, populated or not populated area) and the emergency procedures (need for an independent flight termination system) were defined in accordance with the achieved V&V. Today the V&V has been achieved at 100% enabling flight over low density populated areas with geofencing.

Figure 11: Illustration of the OPV as a tool to pave the way for the UAS – sea trial campaigns

THE FLIGHT ENVELOP OPENING IN PRACTICE: FOCUS ON INITIAL FLIGHTS/AUTOPILOT TUNING AND SHOL OPENING

<u>Initial Flights / Autopilot Tuning:</u>

It was decided since the beginning of the development to rely only on highly assisted modes. The lowest assistance provided was a TRC mode ([7] for response types definition). Direct control or lowest level of assistance like Rate Command / Attitude Hold (RCAH) or Attitude Command / Attitude Hold (ACAH) commands were assessed too risky for remote piloting. The drawback of such approach is that the remote pilot could not recover the aircraft as he would do on a manned helicopter in case of a stability or vibration issue.

A solution to this paradox was to give sufficient authority to the pilot for some specific manoeuvers to recover main feared event. For instance, for first take-off and landing, the pilot had full autority on the collective axis (possibly over power protection) so that he could bring back the helicopter on ground quickly in case of horizontal drift or ground resonance.

The procedure for the tuning of the autopilot controllers is described in figure 11:

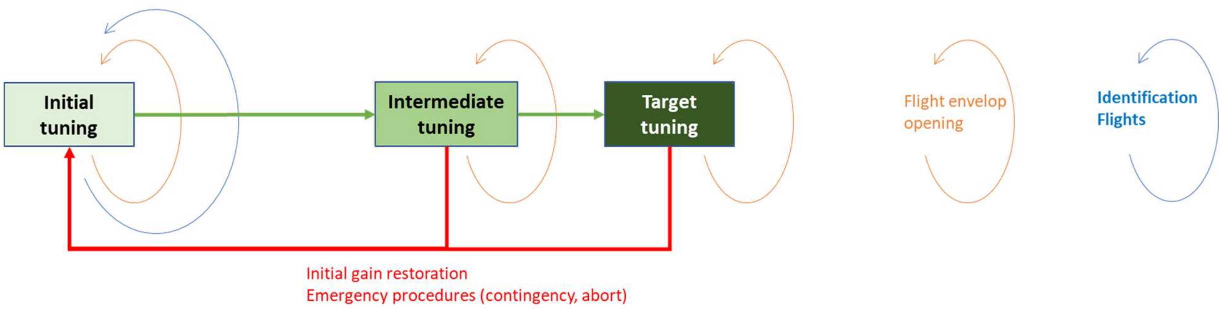


Figure 12: Bode diagram of pitch axis

Opening forward and lateral flights was done with a first autopilot tuning computed in simulation.

This tuning is intentionnally smooth with low gain at high frequency (above 2Hz) so that the risk to re-inject vibration modes is low.

This tuning enables opening the speed envelop in calm wind conditions and to perform a first set of identification flights. Identification flights consist in calibrated stimulations at rotor level applied on the commands around trim conditions. These identifications enable to derive an accurate modeling of the helicopter response and then to refine the tuning of the controllers. The stimulation must be rich enough in terms of frequency band while keeping trim conditions (for example hover). Usually, two controllers tunings are proposed: a target one and an intermediate one basically in between the initial tuning and the target tuning. The intermediate tuning does not have the same performances as the target one but it enables to follow a progressive approach since it is less prone to unexpected behaviours. Note that for UAV's with ship operations, the target tuning exhibits very high performances not comparable with standard controllers tuning for manned helicopters (for which a trade off between performances and comfort is taregted) . A specific procedure enables to come back to the safe and smooth tuning instantaneously in case of stability issue with the new tuning. In case of emergency procedures (like a contingency pattern following a datalink loss), a reversion to the initial safe tuning is also automatically commanded by the system.

The following figures shows typical controllers starting the from initial low gain controller in blue, going through the more performant black controller and ending with the optimized red one.

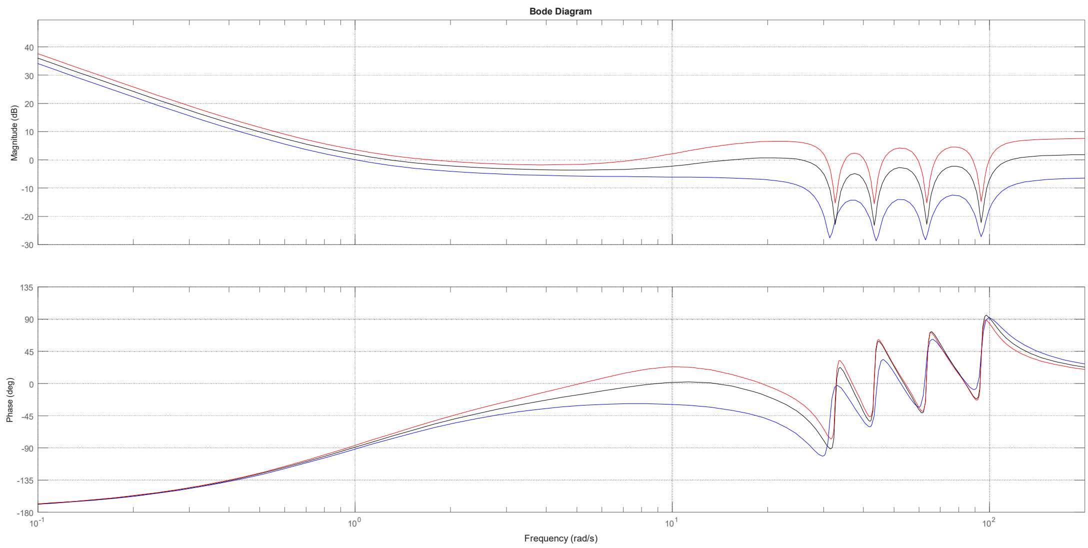


Figure 13: Bode diagram of pitch axis

<u>New functions:</u>

A similar approach was used when it comes to creating or improving significantly a piloting mode.

As already described, the development logic of the piloting modes relies on several testing means. A new function is first tested in simulated and then on OPV with a safety pilot on board and finally on the UAV prototype. Nevertheless, it is also interesting to foresee on the UAV some dissimilarity in order to be able to recover from an erroneous behaviour of the piloting mode at test. The following figure illustrates this principle:

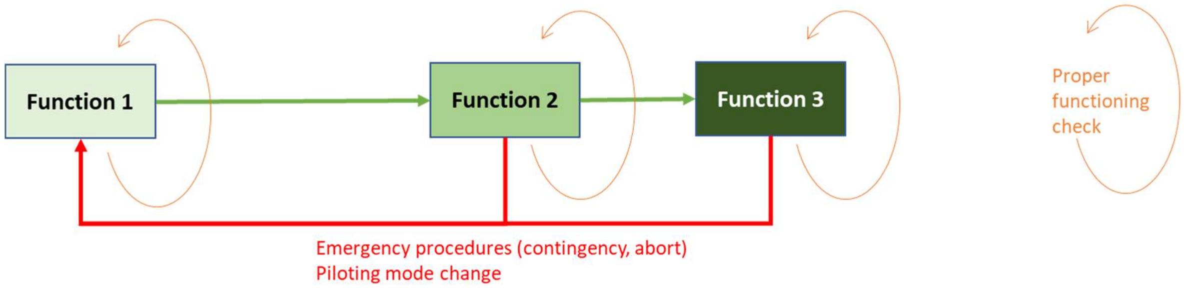


Figure 14: Development principles of a function

Like for the tuning, starting from a secured piloting mode (Function 1), the new or modified function (Function 2 and then Function 3) is tested with a possibility to revert manually or automatically (in case of emergency procedure) quickly to a safe piloting mode (Function 1).

Two examples are given:

Piloting mode	Function 1	Function 2	Function 3	Comments
Take-Off	Hover mode with joystick relying on ground speeds only	Take-off version 1 relying on ground speeds and positions	Take-off version 2 relying on ground speeds and positions and relative positions to the landing spot	Control laws and sensor dissimilarity Function 1 requires datalink
Navigation	Robust and simple navigation	Improved navigation with a 1st set of new features (e.g relative navigation)	Improved navigation with a 1st set of new features (e.g smart wind management)	Control laws dissimilarity Function 1 also used for contingency

Some specific modes have also been developped for some specific development needs like magnetometer in flight calibration, identification flights.

<u>SHOL (Ship-Helicopter Operating Limits):</u>

Opening the take-off and landing flight envelop of the UAV over the ship was also a change of paradigm compared with the classical opening of SHOL. This comes from the following:

- The ship take-off and landing strategy followed by the system is not the same as on a piloted helicopter [8] [9]
- The awareness from a moving ship is degraded even for the visual deported GCS pilot since on a ship the “ground” is moving and this could alter good perception of UAV motions
- Strong safety objectives since the crash on the ship was rated hazardous to catastrophic depending on the crash area.

To cope with these challenges, the following was set up:

- Procedures including roles and respsonsibilities, expected behaviours and emergency actions were defined
- Clearance distance from ship structures was defined. This distance was based on an extensive failure assessment campaign done in simulation and during which all the possible failures (system and vehicle) were assessed together with automatic abort triggered either by the system (system monitoring) or by a ground operator (ground monitoring).
- Decision height was defined: below a certain height, it was assessed preferable to let the UAV complete the landing even if something seems to go wrong.
- Dissimilar abort mode was implemented: in case of unexpected behaviour of the automatic landing mode, this mode enables to move the helicopter away from the deck. The availability of this mode is ensured since it is independent of the sensors used for the ship landing and it is relying on dissimilar control laws.

Figure 14 describes the approach to define the safety procedures to be applied during the SHOL opening.

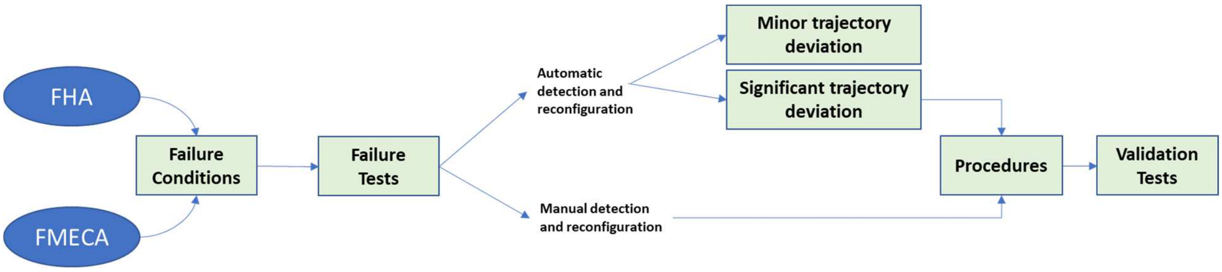


Figure 15: Safety approach for ship landing tests

Based on the FHA and FMECA, the failure conditions are identified and failure tests are performed in simulation. The tested failures are intended to be exhaustive and to cover any failure type (detected loss, hardover, drift) at any equipment (sensors, actuators and computers).

The failures can be ranked in two categories:

- The failures that are passivated automatically and for which the autopilot either reconfigures and continues the sequence (take off or landing) or triggers an Abort.
- The failure that are not passivated at the time of SHOL opening and for which a ground operator recovery action is expected

For both categories, only the failures with a trajectory deviation that could lead to a collision are kept. Based on the trajectory deviations, a procedure is defined. This procedure specifies the deviation for which an action by the operator is required and the type of recovery. The deviation could be monitored either with visual cues by the operator in visual contact and/or a display relying on an independent position measurement.

Then the procedures are validated on the system bench.

CONCLUSION

The flight domain opening of the VSR700 has not been only a challenge to open a flight domain by itself. It has allowed Airbus Helicopters to open a new functional domain: opening a flight envelope of an UAS. This maturity on flight test technique can now be applied on new projects, such as dronizing other existing helicopters.

The flight envelope opening test campaign of the VSR700 was completed after 120 flight hours of unmanned flight tests. This included:

- Initial hover flights
- Opening of the flight domain based on the Cabri G2 flight domain
- Opening an alternate flight domain (alternate gross mass, power upgrade, variable NR)
- Sea and deck landing demonstrations

The opened SHOL domains allow to operate the VSR700 on ships. Results are classified. It has allowed to start developing a new appliation (uncrewed H145 [10]).

ACKNOWLEDGMENTS

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