Convertiplane Control: Assessment of the Collective and Throttle Lever (CATL) in Pilot-in-the-Loop Simulations

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The paper follows the development of the innovative thrust inceptor called the Collective and Throttle Lever (CATL) at the Center for Aviation at the Zurich University of Applied Sciences (ZHAW) in collaboration with the Leonardo Helicopter Division (LHD). The CATL was tested in the ZHAW real-time simulator by LHD Test Pilots after the implementation of several modifications discussed and agreed upon with the partner company. The results of the test indicate that the CATL has significant potential in the convertiplane market, in particular for use in a "lead-in" training platform.

Acronyms

AP	Airplane
CATL	Collective and Throttle Lever
CLAWS	Control Laws
COL	Collective Axis
HC	Helicopter
KCAS	Knots Calibrated Airspeed
LHD	Leonardo Helicopter Division
MFD	Multi-function Flight Display
PFD	Primary Flight Display
ReDSim	Research and Didactics Simulator
RPM	Revolution Per Minute
SAS	Stability Augmentation System
TCL	Thrust Control Lever
THR	Throttle Axis
UDP	User Datagram Protocol
VTOL	Vertical Takeoff and Landing
ZHAW	Zurich University of Applied Sciences

Introduction

Compound helicopters and convertiplanes offer advantages over traditional helicopters, particularly in higher cruise speed, longer range, and fuel efficiency. These benefits are critical in applications like emergency medical services, where rapid response times are vital. This project aims to enhance flight safety by developing a human-centered interface that aligns with pilot capabilities and limitations, reducing human error. The project fits into the helicopter industry, which is exploring compound helicopters and convertiplanes. The former uses auxiliary propulsion to increase forward speed, while the latter can transition between helicopter and fixed-wing mode. Relevant examples, displayed in Figure 1, are the Boeing V-22 Osprey, AgustaWestland AW609, Airbus Helicopter X3.

While traditional helicopters and airplanes use familiar control mechanisms (collective lever for rotor thrust and throttle lever for propeller thrust), determining the optimal thrust inceptor for convertiplanes is challenging due to changing thrust axis directions.

Figure 1: Convertiplane and Compound Helicopters

Traditional helicopters use a collective lever for rotor thrust, while fixed-wing aircraft use a throttle lever for propeller thrust, both offering intuitive control. However, in convertiplanes, the pilot needs to control both thrust types with the same inceptor. Issues like "collective dyslexia" can arise when rotorcraft pilots operate convertiplanes, especially during critical situations [Whittle-2011]. Further attention must be paid to thrust control during the transition phase from airplane (AP) to helicopter (HC) mode and vice versa, where the thrust axis lies between the aircraft's longitudinal and vertical axes.

To avoid this kind of situation, Capone et al. [Abà-2023], introduced an innovative thrust inceptor called Collective and Throttle Lever (CATL), developed since 2015 at the Zurich University of Applied Sciences (ZHAW). The CATL combines a human-centered pilot interface with fly-by-wire technology to reduce pilot workload and enhance safety. The conceptual phase of the CATL was entirely funded internally by the ZHAW Centre for Aviation. The primary objective of the initial phase was to create a single lever that combines both collective control and throttle functions. The basic initial assumptions are listed here:

- During conversion, the motion of the lever shall be unambiguous, i.e., only vertical or horizontal
- Switching between different modes (AP / HC) occurs when the nacelle's angle is at 60 deg
- Conversion is initiated by the pilot through dedicated nacelle command switches
- Conversion status is monitored by the flight control system and presented to the pilot at any moment via Primary Flight Display (PFD) or Multi-function Flight Display (MFD), as well as aural warnings
- It shall be possible for the pilot to abort the conversion at any time during the maneuver.

Kinematics studies involved intense research and testing. Figure 2 shows the final concept, on the left in HC Mode (vertical motion), while on the right AP Mode (horizontal motion). The green and red circles indicate free or fixed joints. It is a versatile four-joint coupling system that allows both AP and HC control motions by fixing one lever.

To offer natural movements in the two different flight modes, the range of the handle motion (back / forth or up / down) is based on popular helicopter and airplane configurations.

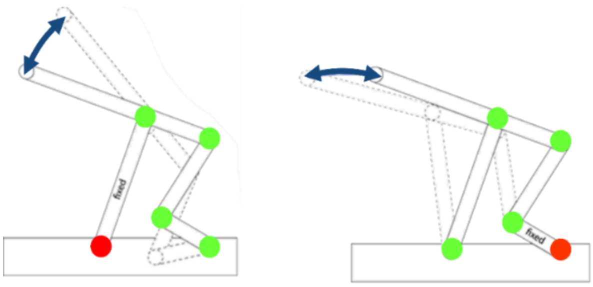

Figure 2: CATL final concept

A study on general ergonomics considerations was also performed, resulting in a final grip design that accommodates several switches duplicated for both hand positions (see Figure 3). The CATL was also equipped with two encoders to read the position of the two shafts, enabling closed-loop control. The final fully functional prototype is depicted in Figure 4.

After an initial phase of testing, the CATL was integrated with a real-time simulation model of the XV15. The model originates from the work of Ferguson on the Generic Tiltrotor Simulator [Ferguson-1988]. The complete tilt-rotor model was integrated into the ZHAW simulator ([Barra et al-2019], [Abà et al-2020], and [Barra et al.-2022]). The CATL was integrated in the ZHAW Research and Didactics Simulator (ReDSim) to replace the standard collective control used in XV15.

When the nacelles are at a 90° angle – i.e., in HC Mode – the pilot uses conventional collective-like controls by pulling and pushing the CATL to perform the desired mission.

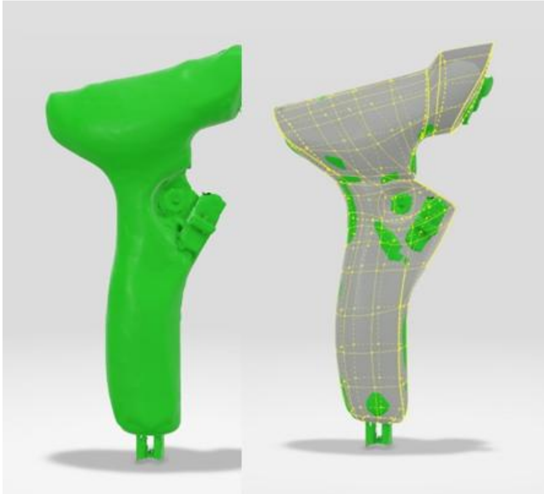

Figure 3: CATL Grip

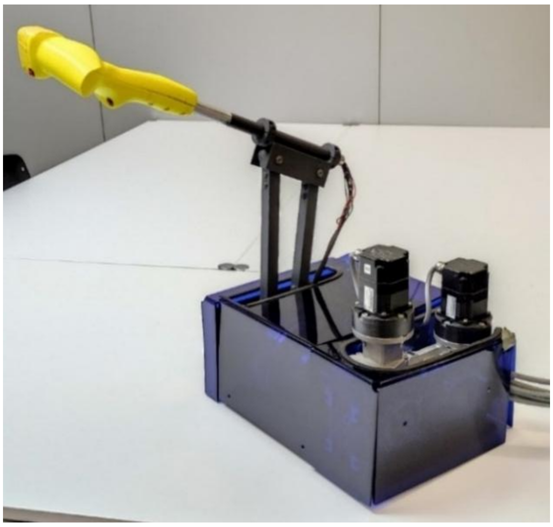

Figure 4: CATL fully functional prototype

Conversely, when flying in AP Mode, i.e., with the nacelles at a 0° angle, the CATL works as a typical throttle lever. With respect to a convertiplane equipped with a standard lever, such as a collective or a throttle, the conversion phase, in terms of speeds and nacelle angles, remains the same, with the only difference that the pilot has to switch hand position from collective- to throttle-like control. A hysteresis mechanism is used to switch between the two modes to prevent continuous switching.

In [Abà-2023], a specific mission was designed in order to facilitate the evaluation of the CATL features. The test sequence was composed of takeoff and hover in HC Mode, conversion HC to AP, perform two circuits in AP Mode, conversion AP to HC, and landing in HC Mode. One important finding was that a proper evaluation of the CATL was not entirely possible. In fact, the pilot was already task-saturated by the conversion procedure. A thorough analysis of the results highlighted two main issues. On one side, the XV15 thrust model in AP Mode was not sufficiently accurate and realistic. On the other hand, the set of used control laws were not completely suited for the task at hand. This paper describes the next steps in the CATL development and presents the results of a new series of pilot-in-the-loop tests.

Model Improvements

The first task was focused on the improvement of the XV15 model. As already mentioned, an issue was given by the non-realistic thrust response of the aircraft in AP Mode. In order to fix this problem, a complete review of the simulation model has been performed based on available information and literature. Particular emphasis was given to the thrust axis in AP Mode.

Reconfigurable Display

During the first set of tests, it became evident that the used display missed a significant amount of information that is instrumental to the test. Additionally, another problem that generally arises when performing this kind of investigation in real-time simulators is the need to modify the display “on the run” while the test is performed. To cope with this last issue, the display was developed with the Matlab App Designer® tool and complemented with in-house UDP communication to exchange data between the simulation model running in Simulink and the instrument.

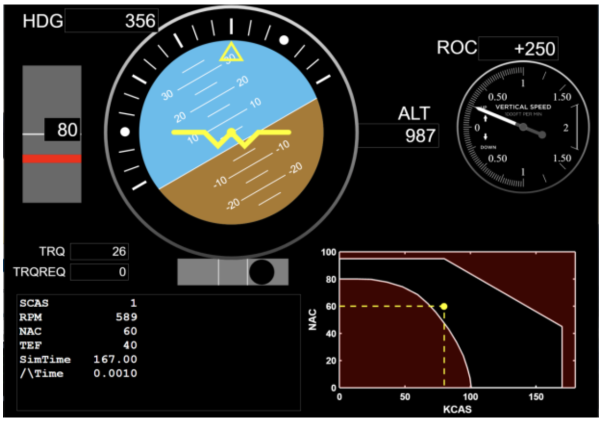

Figure 5: New Instrument Panel

The obtained display is shown in Figure 5. Besides the usual information such as airspeed, altitude, rate of climb, heading, horizon and turn coordination, a few more specific information was needed, such as:

- Display of airspeed corridor limits (a red and blue line for max and min airspeed) together with the current airspeed indication
- Predicted and actual torque values in percent
- Conversion corridor in terms of airspeed and allowed nacelle angle

Visual System Modification

The visual system of our flight simulator was modified to include a second aircraft within the simulation environment. Figure 6 shows the ReDSim cockpit and the modified scenario.

Figure 6: ReDSim with the second airplane (right).

This additional aircraft enables scenarios such as formation flying, aerial refueling, or pursuit/chasing tasks. Its trajectory is defined by a pre-recorded flight path, which can be derived from a previously executed maneuver.

To initiate a seamless test scenario, the second aircraft trajectory can be triggered either from the simulator host or by the co-pilot. Prior to the start of the maneuver, the second aircraft is positioned directly ahead of the pilot aircraft, aligned at the same altitude and separated by a predefined distance. When the test is ready to begin, the co-pilot activates the sequence, causing the second aircraft to follow its programmed flight path autonomously.

Initial speed and altitude of the second aircraft are matched to the pilot's current flight parameters to ensure a smooth transition. As mentioned, one of the tasks could be to chase the second aircraft. Therefore, once the maneuver begins, the pilot is asked to maintain visual contact and follow the second aircraft throughout its predefined trajectory.

CLAWS Modifications

The first improvement to the control laws consisted of a modified approach for the governor in airplane mode. A torque reference was computed based on the collective command, and the corresponding error was fed to a PI controller with gains scheduled according to the nacelle angle. Additionally, a feed-forward path was added to the controller to improve the overall response. The modified control laws are shown in Figure 7. This simple approach provides a more realistic thrust axis response in airplane mode.

Another modification of the CLAWS was on the required conversion corridor. The upper part of the corridor (see Figure 8) was simplified by cutting part of the upper boundary. The original schedule did not seem realistic from an operating point of view, allowing operation at 90 degrees of nacelle’s angle (HC Mode) up to circa 130 kts. Operation around the upper limit also resulted in a high workload for the pilot, given the reduced range of airspeed in which the conversion from 90 to 40 degrees was constrained.

Some Handling Qualities verifications at high speed, where the Turn-Coordination mode is active, showed that the lateral-directional damping was less than ideal.

The problem was fixed by adding yaw rate damping feedback to the directional SAS when the turn-coordination mode is active.

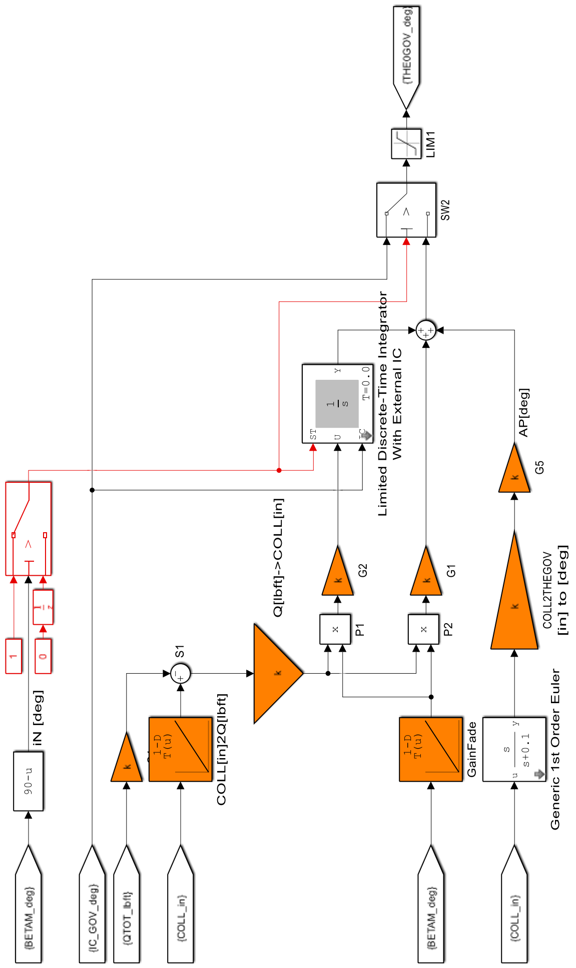

Figure 7: New Governor

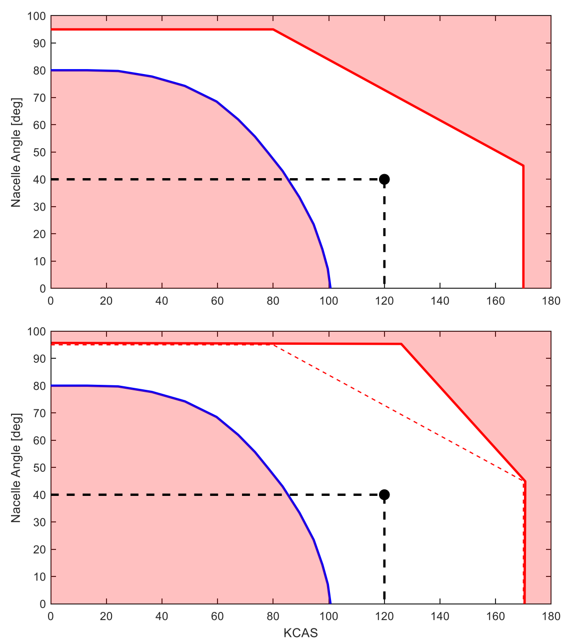

Figure 8: Modified XV15 Conversion Corridor (original bottom, modified upper)

A review of the nacelle command was also carried out. The nacelles are controlled by the thumbwheel on the grip of the CATL. Pressing a thumbwheel in one direction will force the nacelle to move in discrete steps, precisely from 0 to 60 degrees and from 60 to 90.

With reference to Figure 9, the original CATL logic set the unit in HC Mode (D1 in command and D4 “frozen”) or in AP Mode (D4 in command and D1 “frozen”) at around 60 degrees with an hysteresis of 5 knots, as shown in Figure 10.

Following the above logic, the engagement of HC or AP Mode was obtained in a single press of the thumbwheel. At the request of the test pilot, the logic was modified to require two presses of the thumbwheel to pass from AP to HC Mode, while only one press is now required to pass from AP to HC Mode. The modification was simply obtained by changing the hysteresis entry and exit points from the old 55 and 65 to 57 and 59 degrees of nacelle angle (see Figure 11).

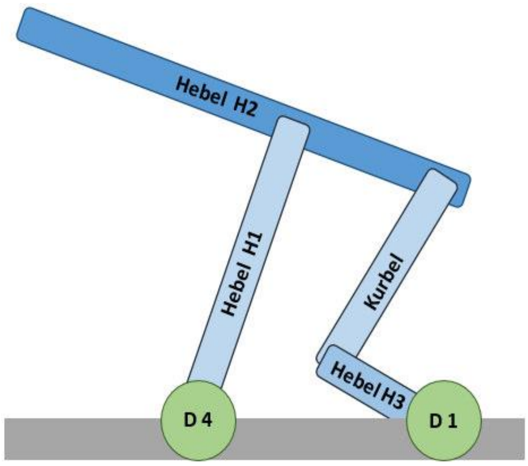

Figure 9: CATL Elements

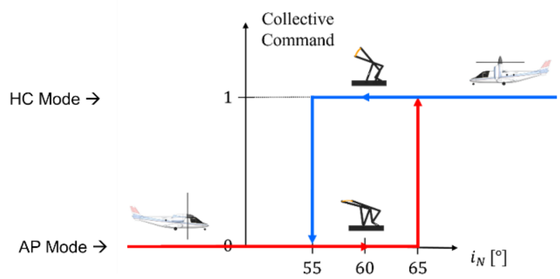

Figure 10: Old CATL Mode Logic

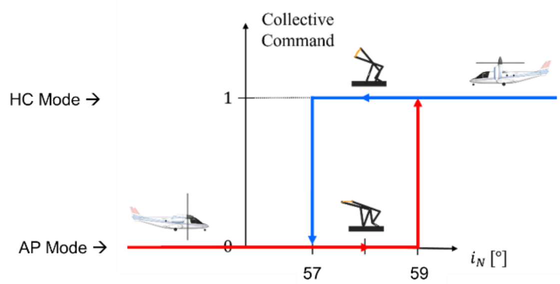

Figure 11: New CATL Mode Logic

In the above description of the CATL modes of operation, we said that while the unit is in HC Mode, the node D4 is “frozen” and that while the unit is in AP Mode, the node D1 is “frozen”. This is not completely correct, and this is why we have put this in quotes. The inherent redundant nature of the CATL allows us to plan in case of a seizure of one of the CATL axes:

- the *Collective* axis (node D1), named COL.
- the *Throttle* axis (node D4), named THR.

In case of a seizure of one of the two CATL axes, the aircraft can still be safely piloted by using the remaining one, provided that this remaining one is in a position coherent with both positive and negative commands at the moment in which the failure occurs. This is obtained by driving the non active axis in its middle position, depending on the nacelle’s angle. The situation is represented in Figure 13.

It follows that during normal operation of the CATL, while the Collective axis (D1) is in command, the node D4 will be moved to have the Thrust axis in the optimal position for a possible failure. The same happens when the Throttle axis (D4) is in command and the node D1 is driven to a specific position.

Consequently, one of the open questions of the test was also to verify that the commanded motion of the axis not in command did not interfere with or create any possible confusion for the pilot.

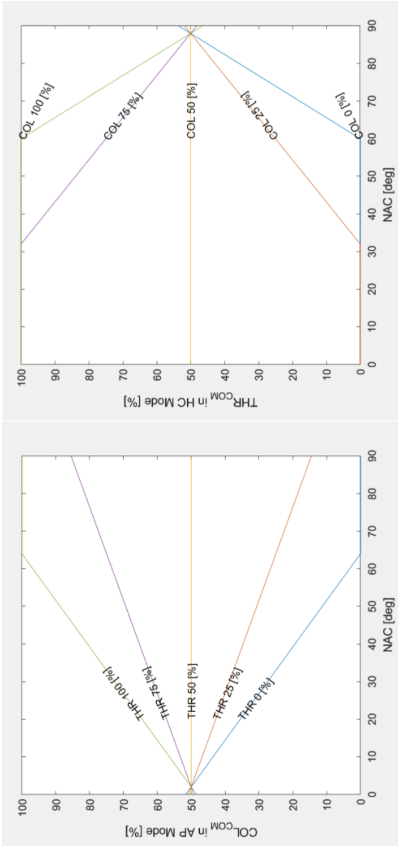

Figure 13: Command to Axis that is not control (command to throttle axis above and to collective below)

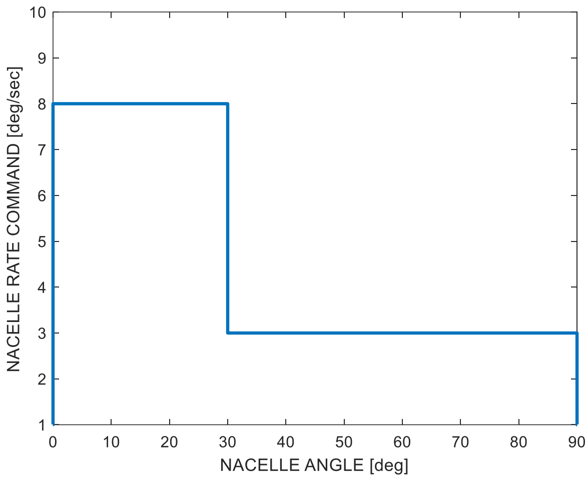

Figure 12: Nacelle Rate Command

The last modification of the CLAWS was the commanded rate of the nacelle. The original commanded rate was about 8 deg/sec for nacelle angle between 2.5 and 87.5 degrees. This resulted in a rather high workload for the pilot to control altitude between 0 and 60 degrees, especially when transitioning from HC to AP Mode, where the loss of thrust corresponds to a significant loss of altitude during conversion. To this end, the commanded rate schedule was modified as per Figure 12. The new commanded rate for nacelle angle between 0 and 60 degrees is now 3 deg/sec.

Test Setup and Results

As already mentioned, during our preliminary simulation tests [Abà et al-2023], only helicopter pilots were used; this resulted in an ineffective evaluation of the CATL. Therefore, in order to effectively assess the inceptor, tests with a tiltrotor pilot were conducted for a more accurate evaluation of handling qualities and workload.

Two different tests were performed. The first test consisted of an aerodrome circuit task. One additional objective of this task was also to allow the pilot to familiarize himself with the CATL. The second test consisted of chasing an aircraft and flying in close formation with it. During this task, the pilot must adjust the thrust setting via the CATL. The objective of this second task is to carry out an effective evaluation of the thrust axis handling qualities in AP Mode.

A tilt-rotor is a complex machine, and its handling qualities heavily depend on the effectiveness of the adopted set of control laws. Even if the focus of the trials was not on the control laws, it was soon discovered that these played a significant role in the evaluation of the CATL. Given the non optimal status of the current control laws, the performed tasks always resulted in a high workload. Therefore, even if the initial idea was to assess both handling qualities and workload using the Cooper-Harper [Cooper et al. 1969] and the Bedford [AGARD 233] scales, due to the high workload, it was decided to focus only on pilot workload.

Aerodrome Circuit Task

The aerodrome circuit consisted of the following phases: taking off in HC Mode, converting the tilt-rotor from HC to AP Mode, performing the aerodrome circuit (climb, downwind, base, and final), switching back to HC Mode, and landing.

Initially, the task was flown with the CATL either with only Collective functionality active (COL in command, node D1 active) or with only Throttle functionality active (THR in command, node D4 active). Eventually, the circuit was flown with the two CATL modes combined.

During the tests where only one feature of the CATL was used, and the tilt-rotor was flown in both AP and HC Mode, the pilot reported more difficulties during HC operations when using the THR. While hovering, he made some mistakes with altitude changes, leading to potentially hazardous conditions. On the contrary, flying the XV15 in AP Mode with COL was more straightforward. This can be explained on one hand by the fact that, in general, in AP Mode, the pilot needs to adjust the thrust less than in HC Mode. On the other hand, the familiarity of the pilot with an Only-Collective solution may also have played a role.

Chasing task

Chasing a plane or flying in formation is a typical task for military operations, for fixed-wing fighters or trainers. Luckily, our test pilot was also familiar with these tasks, even though he had never performed them with a tilt-rotor.

The chasing task starts with the two aircraft flying in formation, with the chaser XV15 behind the chase aircraft. The task is to follow the chase aircraft as precisely as possible.

Figure 14: Chase Task in the ReDSim

In order to define an achievable task for the chasing aircraft, the trajectory of the chase aircraft was obtained by recording a piloted simulation.

Even in this case, tests were performed with either THR or COL in command. In both cases, the task was performed successfully and reported here:

- THR in command: Bedford 5 – moderate workload, acceptable performance.
- COL in command: Bedford 6 – high workload, borderline performance acceptability.

In general, using THR in command was considered more effective and intuitive when chasing the lead aircraft. As shown in Figure 15 and Figure 16, the distance between the lead aircraft (red) and XV15 (blue) was smaller when the THR in command was used.

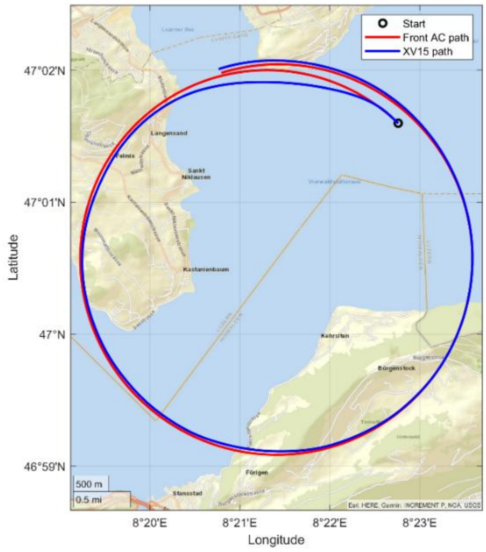

Figure 15: Chase test THR in command.

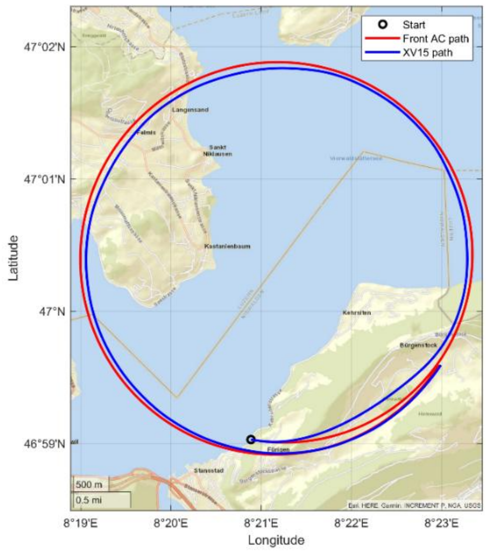

Figure 16: Chase test COLL in command.

Limitations

Despite the promising concept, several limitations emerged during the tests at the ReDSim. The first limitation, which has already been mentioned, is the lack of an advanced and efficient set of control laws to complement the CATL functionalities.

From a hardware perspective, the current prototype needs some improvement, particularly with respect to the lever travel and its mechanical characteristics, such as free-play and friction. The high friction on the THR (node D4) axis makes fine control particularly difficult, leading to a tendency to confuse expected control outcomes under high workload conditions.

Another hardware concern is the duplication of certain switches, which increases cognitive load and the risk of errors.

The beep response, used for trim or fine adjustments, was also reported as not optimal.

Finally, while the selected formation task effectively evaluates the CATL, it does not represent typical tilt-rotor mission profiles, which biases the validity of the results.

Potentialities

Despite its current limitations, the CATL demonstrates good potential as a hybrid control interface for VTOL configurations. One of its key advantages is the intuitive nature of its dual-mode operation, which allows natural pilot movements and helps reduce control errors, particularly during Nap-of-The-Earth Operation.

Another interesting feature of the CATL is its implicit redundancy, enabling pilots to operate exclusively in COL or THR in command modes in case either one of the two functionalities is lost.

The marked difference in the aircraft required response between the AP and HC Modes highlights the CATL's versatility, making it especially valuable in aircraft that must operate effectively across a wide flight envelope, such as tilt-rotors or compound helicopters. In fact, the CATL can be optimized separately for the COL and THR responses in terms of travel, forces, frictions, etc.

CATL flexibility makes it a strong candidate for use in experimental or training platforms, where exposure to both control paradigms is crucial for pilot training.

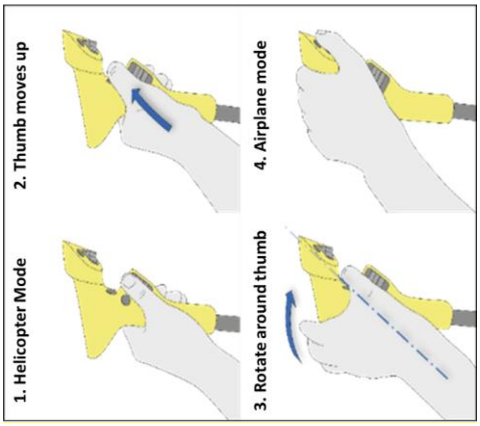

Figure 17: CATL Dual-Grip Layout

The CATL features a dual-grip layout to reduce AP/HC Mode confusion between THR/COL control inputs (see Figure 17). The pilot emphasized that this design choice was beneficial, in particular in high workload scenarios, minimizing the risk of accidentally performing a movement in the wrong direction.

Conclusions

The testing of CATL in the ReDSim with a professional tiltrotor pilot revealed both promising capabilities and critical areas for improvement. The dual-mode concept, enabling both collective-like and throttle-like control, proved to be a viable and intuitive solution, particularly effective in reducing pilot errors during complex operations. The ergonomic design, i.e., the dual-grip layout, was highlighted as a strength in high-workload scenarios, helping to minimize confusion between HC and AP control modes. Pilot feedback confirmed that THR control was preferable in formation tasks, whereas COL mode was better suited for hover and vertical maneuvering.

One of the biggest limitations of the current solution was the lack of an ad-hoc designed set of control laws that would allow the full exploitation of the potentialities of the CATL. Hardware-related limitations, such as high friction on the THR axis, represent significant barriers to optimal performance. Additionally, while the formation task allowed for detailed control evaluation, it did not fully match typical tilt-rotor operations, which somewhat limited the broader applicability of the results.

Despite these drawbacks, the CATL's flexibility, intuitive interface, and adaptability across different flight phases make it a promising inceptor for next-generation tilt-rotor and compound rotorcraft platforms. Its potential use in experimental or training platforms deserves further investigation, along with refinements to hardware and control laws design to fully develop the potentialities of CATL.

Future work on CATL will include:

- Complete redesign of the hardware, reducing free-play and friction
- Design a set of advanced dedicated control laws to fully exploit the potentialities of the CATL
- Completion of the ongoing safety analysis to highlight possible weaknesses of the design from a safety point of view.

Acknowledgements

The authors would like to thank Leonardo Helicopter Division for its for supporting this work.

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