Convertiplane Control During Transition: the Collective and Throttle Lever (CATL)

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ABSTRACT

Control of convertiplanes during transition is a challenging task. This work focuses on the development of the interface between the pilot and the flight control thrust axis command. The goal is to provide the pilot with an ergonomically well-designed and intuitive inceptor and thus, minimizing human errors and increasing flight safety. 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 from 2015 to today. The various phases of the CATL development are described starting from the concept phase, continuing with the development of the prototype and its integration with the XV15 simulation model and a real-time simulator and concluding with the description of the preliminary testing and results. The obtained positive results provide some insight into the problem. Further investigations and trials are needed for a more thorough assessment of the inceptor. These will be the subject of future works.

Acronyms

AP	Airplane
ARINC	Aeronautical Radio, Inc.
CAS	Command Augmentation System
CATL	Collective and Throttle Lever
CHR	Cooper Harper Rating
CLAWS	Control Laws
CYTS	Collective and Yaw Trim Switch
FCS	Flight Control System
FTR	Force Trim Release
GRTS	Generic Tilt-Rotor Simulator
HC	Helicopter
HQ	Handling Qualities
KES	Kill Emergency Switch
KIAS	Indicated Airspeed kt
MFD	Multi-function Flight Display
MTE	Mission Task Elements
MTOM	Maximum Take Off Mass
NCT	Nacelle Control Thumbwheel
PFD	Primary Flight Display
PI	Proportional Integral Controller
PLC	Programmable Logic Controller
ReDSim	Research and Didactics Simulator
RPM	Revolution Per Minute
SAS	Stability Augmentation System
SCAS	Stability and Command Augmentation System
TCL	Thrust Control Lever
ThAx	Thrust Axis
UDP	User Datagram Protocol
VAC	Visual Approach Chart
VTOL	Vertical Takeoff and Landing
ZHAW	Zurich University of Applied Sciences

Symbols

i_N	Nacelle incidence	[deg]

1 Introduction

Compound helicopters as well as convertiplanes have significant advantages with respect to helicopters. For example, emergency medical services would benefit from faster-traveling speed and greater range compared to conventional helicopters. In case of accidents, a short response time is vital to the health of the patients. Similarly, when patients or organs are transferred between hospitals and specialist medical centers, a short transfer time can be crucial. A similar rationale can be applied to other services such as search and rescue or homeland security.

Figure 1: Convertiplane and Compound Helicopters

By approaching the development of the interface between the pilot and the flight control system with a human-centered design, this project focuses on the pilot's capabilities and limitations. Providing the pilot with an ergonomically well-designed and intuitive cockpit control is an efficient way to minimize human errors and thus increase flight safety.

The helicopter industry is currently advancing in the field of compound helicopters and convertiplanes. A compound helicopter is a helicopter with an auxiliary propulsion system that provides thrust in excess of that which the rotor(s) alone could produce, thereby permitting increased forward speeds. This aircraft may or may not have a wing to reduce the lift required from the rotor system. A convertiplane is an aircraft that uses rotor power for Vertical Takeoff and Landing (VTOL) and converts to fixed-wing lift in normal flight.

Notable examples of such concepts are (see above): Boeing V-22 Osprey, AgustaWestland AW609, Airbus Helicopter X3, Piasecki X-49A, Sikorsky X2 and the Next Generation Civil Tiltrotor (NGCTR).

By using different means to generate thrust or lift in forward flight, compound helicopters and convertiplanes are potentially more efficient than helicopters. These aircraft can also cruise at faster speeds than conventional helicopters while still being able to take off and land vertically.

“Since the earliest days of manned flight, designers have to sought to assist the pilot in the performance of tasks by using stick and feel systems to bring these tasks within the bounds of human physical capabilities” [AGARD332 1997]. For this reason, many performance and handling qualities specifications currently in use by civil and military organizations set specific and quantitative requirements for such devices.

In a helicopter, the pilot controls the rotor thrust by using the collective lever. Pulling up the collective will increase the thrust generated by the rotor. Pushing down the collective will decrease the thrust generated by the rotor. Therefore, the command is really intuitive and natural for the pilot. Similarly, in an airplane the throttle lever is pushed to increase propeller thrust and pulled to decrease it. Again, the command is really intuitive and natural for the pilot.

But what is the best thrust inceptor for an aircraft in which the thrust axis direction changes with the flight condition such as a convertiplane? The answer to this question is by no means straightforward, and also related to safety considerations.

For example, the Thrust Control Lever (TCL) installed on the Boeing V-22 Osprey is similar to a thrust lever found on airplanes and is intuitive to use for a fixed-wing pilot. But if a rotary-wing pilot starts to fly the V-22, she/he would intuitively give the wrong TCL inputs. This issue is sometimes called “collective dyslexia” and is potentially a safety critical issue [Whittle et al. 2011]. Especially during hover, due to the close ground proximity, erroneous inputs can have serious consequences. Additionally, even though a helicopter pilot might be able to fly the V-22 without problems during normal operations, it is possible that in situations with high workload, such as emergency conditions or brown/white-outs, the pilot would use inappropriate commands and give the wrong thrust input.

Additional considerations shall also be given to the thrust control during the conversion phase, where the thrust is neither aligned with the longitudinal axis (airplane) nor with the vertical axis (helicopter) and to possible failure conditions during this phase.

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), from 2015 to today. The developed solution is based on both an innovative pilot interface and novel functionalities that can take full benefit of fly-by-wire technology. Fly-by-Wire technology coupled with this innovative concept should decrease the pilot workload and guarantee a better level of safety.

In the following, the various phases of the CATL development are described, starting from the concept study where the functional requirements of the throttle/collective inceptor are defined. This includes the analysis of the different stages of a flight and the corresponding tasks of the pilot. Thereafter, the selection of the eligible solutions is performed. Based on the functional requirements a set of possible solutions have been further developed.

A set of criteria (such as ergonomics, intuitiveness, and reliability) have been defined. Based on these criteria the best solution was selected for further development. For this selected solution a series of mock-ups were developed, converging in the final realization of a fully functional prototype (see Figure 2).

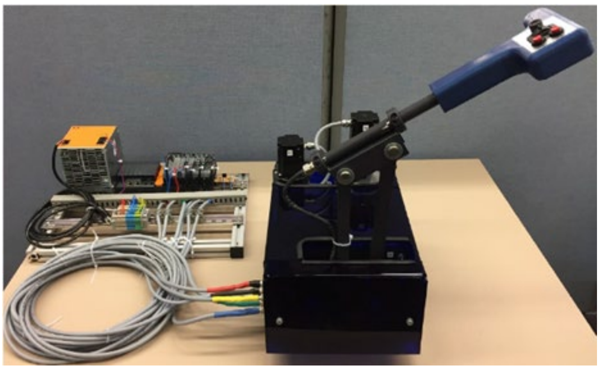

Figure 2: CATL Initial Prototype.

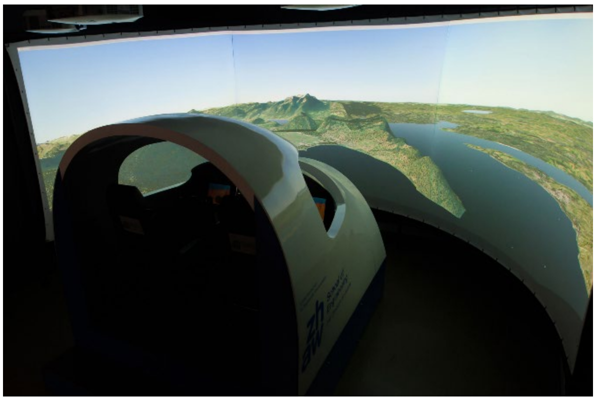

Figure 3: ZHAW simulator ReDSim.

The next phase was the integration of the CATL in the research and development simulator of the ZHAW Center for Aviation, the so-called Research and Didactics

Simulator (ReDSim), see Figure 3. To this end, the CATL was coupled with the in-house developed simulation model of the XV15 [Abà et al. 2020] [Barra et al. 2019] [Primatesta et al. 2022] [Primatesta et al. 2023] [Barra 2022].

The in-house developed XV15 model has been equipped with a set of dedicated flight control laws that have been integrated with the CATL [Bernhardsgrütter et al. 2020] [Briamonte 2022]. The CATL has been designed to also provide a fail-safe scenario for possible / plausible failure conditions.

Flight simulation trials have been carried out with the CATL. The trialing population was fixed-wing and rotary-wing pilots, preferably trained test pilots. The performances were evaluated from collected data and also using a questionnaire, to obtain both qualitative and quantitative feedback.

The obtained results provide some insight into the problem. Nevertheless, the researchers believe that further investigations and trials are needed. These will be the object of future works.

2 Conceptual Phase

The cost of the CATL hardware has been internally funded by the ZHAW Centre for Aviation and supported by the work of several students of the Bachelor in Aviation [Stoll 2022] [Luso et al. 2016] [Lüthi et al. 2017]. In the following paragraphs, a brief summary of CATL development will be given.

2.1 Basic Assumptions

The objective of the project is to have a single lever that integrates both collective control, and throttle lever functions. This would allow the pilot's hand to remain on the throttle lever throughout all flight phases.

Some basic assumptions were defined at the beginning of the project:

- during conversion, the motion of the lever shall be unambiguous, i.e., only vertical or horizontal
- switching between different modes (airplane / helicopter) occurs when the nacelles angle is at 45° (this original assumption was later modified)
- conversion is initiated by the pilot through dedicated nacelle command switches
- conversion status is monitored by the flight control system and status is presented to the pilot at any moment in time 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.

Various ergonomic requirements must be met. Contact points shall be within anthropometric requirements, considering the 5th percentile of women and the 95th percentile of men for helicopter and throttle control devices, as shown in Figure 4 to Figure 7. Contact between hand and lever must never be interrupted during conversion. Based on these measurements, the various solutions envisaged for the CATL can be evaluated.

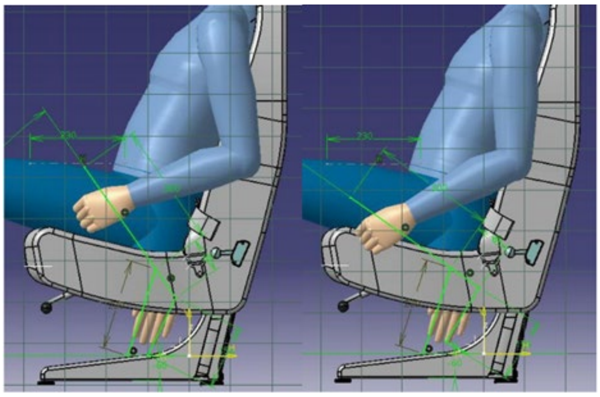

Figure 4: 95th percentile of men in helicopter mode

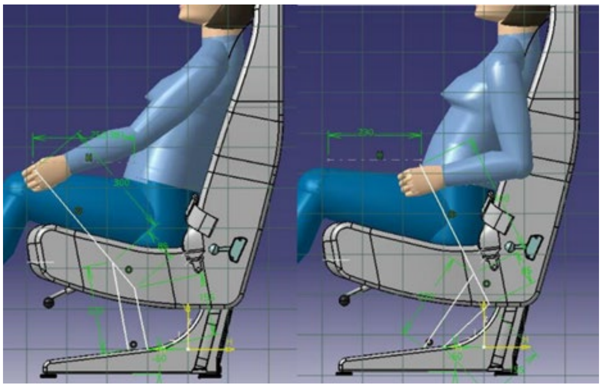

Figure 5: 5th percentile of women in flight mode

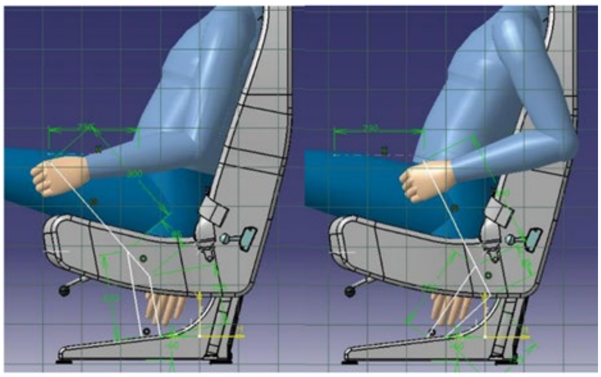

Figure 6: 95th percentile of men in flight mode

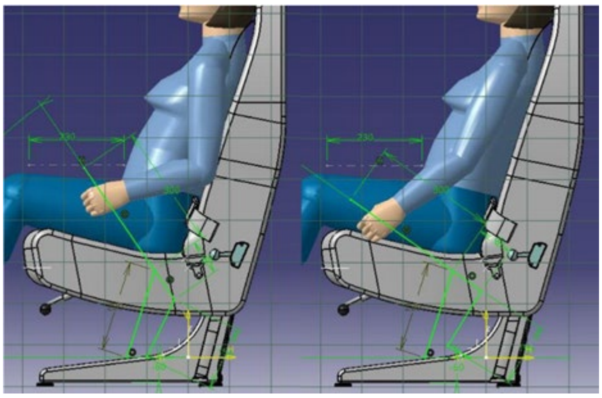

Figure 7: 5th percentile of women in helicopter mode

2.2 Kinematics Studies

The kinematic solution was developed over intense studies and testing of lever systems, rod lengths, angles, and rotations. Several concepts have been devised and assessed. The most promising concept is based on a four-bar linkage such as in Figure 8.
The travel of the handle can be determined by the length and position of the link rods and can thus be adapted to the ergonomic requirements. The handle movement direction (back/forth or up/down) is determined by fixing the angle position of either D1 or D4, depending on the mode of operation (airplane or helicopter). This results in clear and intuitive haptic feedback to the pilot with respect to the flight mode the vehicle is actually in.

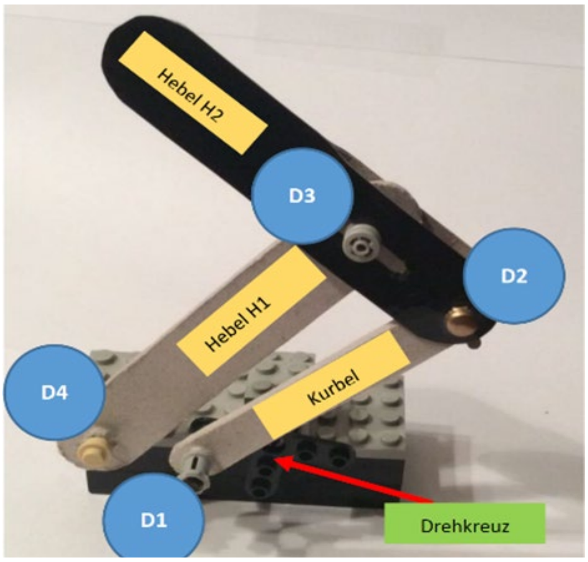

Figure 8: Lever concept based on a four-bar linkage

2.3 Final Concept

The final design incorporates a versatile four-joint coupling system that can be altered by fixing one of the two bottom levers, allowing for the grip motion to be seamlessly changed to accommodate either airplane or helicopter control motions.

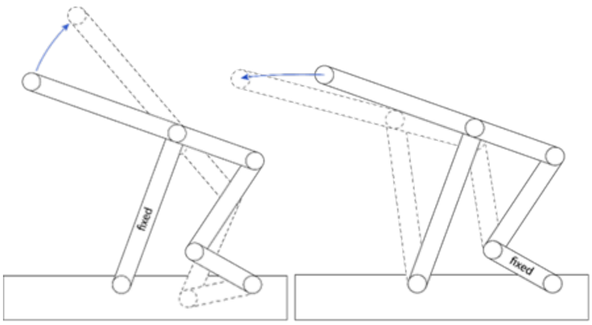

Figure 9: Motion Paths of Helicopter and Airplane Modes

2.4 Grip Ergonomics

Several ergonomics studies were conducted to design a functional grip made of clay with the required control buttons as seen in Figure 10.

The primary goal was to achieve a seamless transition between the two grip positions while ensuring continuous contact with the lever. The transition from one mode of operation to the other is described in Figure 11.

A 3D scanner is used to transfer the model to a CAD program where it was rebuilt to its final design. The obtained model was finally adapted to the required switches and buttons, wiring and mechanical connection to the rod (see Figure 12).

Figure 10: Ergonomic optimization using a clay model

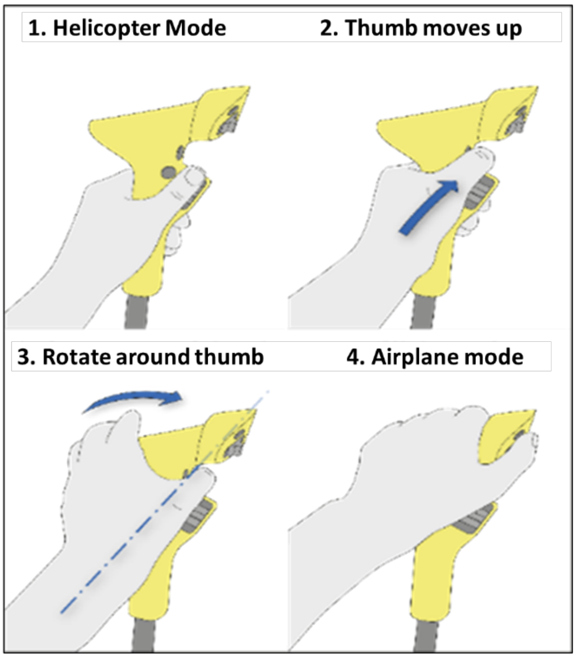

Figure 11: Hand position during conversion

The grip was finally equipped with a series of switches replicated for the two modes of operation. The type and functionalities of the switches will be described later in paragraphs 4.3 and 4.4.

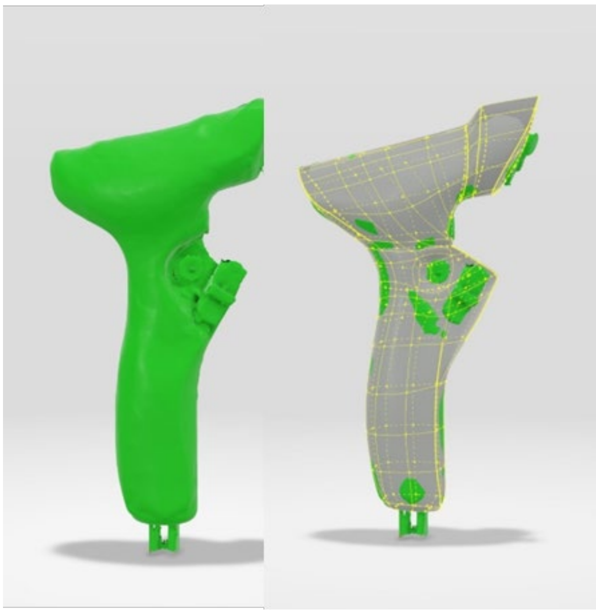

Figure 12: Scanned model as a basis for the final design

3 Prototyping

The prototype phase consisted of the mechanical and electrical design, followed by the initial software development. The first part was dedicated to the identification of components, their sizing, and the CAD model. The goal was to generate a fully functional first prototype originating from the final concept. The following components have been analyzed:

Handle/grip: Since it is the first and only point of contact with the pilot, this is probably the most important component. Particular attention was given to shape, size and switch positions. Grip ergonomics has already been discussed in Paragraph 2.4 while the grip design will be presented later in this paragraph.

Main control lever: Many different options were studied. They differ in the number of components and flange types. Eventually, the final design is composed of a single tube clamped through two bearing flanges.

Intermediate lever/crank: It consists of two milled parts, which are connected by a squared metal tube.

Dampers: The CATL inceptor may need to be dampened during operation. Usually, a certain level of damping may be beneficial for good handling qualities, especially for tracking tasks [AGARD332 1997][SAE-ARP5764]. Nevertheless, damping was considered secondary in this study and not implemented. This decision was also based on previous experience with throttle and collective lever development.

Friction: To provide the classical collective feel to the pilot while the "collective" clutch is open, an additional friction was designed. A brake shoe friction mounted on the drive shaft, which can be individually adjusted with a control wheel, was included in the design (this can also be seen in Figure 13). Later it was eventually removed since the required frictions for both collective and throttle functionalities can be obtained by the two adjustment screws acting directly on the electromechanical clutch assemblies.

Clutches: The force transmission between the two shafts is established or removed by means of two electromechanical clutches. When one of these clutches is open the corresponding motion (collective or throttle) is allowed.

Motors: The drive systems are connected to the front of the drive shafts in the form of a servomotor, which can be decoupled or coupled using electromechanical clutches. The servo motor are used to lock in position or to move the shaft to a desired position.

Drive shafts: Two shafts are mounted between two plain bearings.

Position Sensors: The unit has been equipped with two resolvers that read the position of the two CATL shafts. These are needed to realize the closed-loop control of the unit.

The final prototype is shown in Figure 13 and Figure 14. The base is a rectangle of about 25x35 cm, while the position of the grip was calculated previously to accommodate the pilot's movements. The main components are highlighted: the two motors with their respective gearing, clutches and original friction system coupled to the levers system. Each motor is connected to the lever through its drive shaft, and it can be controlled both independently and simultaneously. Evidently, the current CATL is designed only for lab testing; a flightworthy unit will require a complete redesign to fit weight and envelope requirements while the basic concept of operation and ergonomic functionalities can be fully retained.

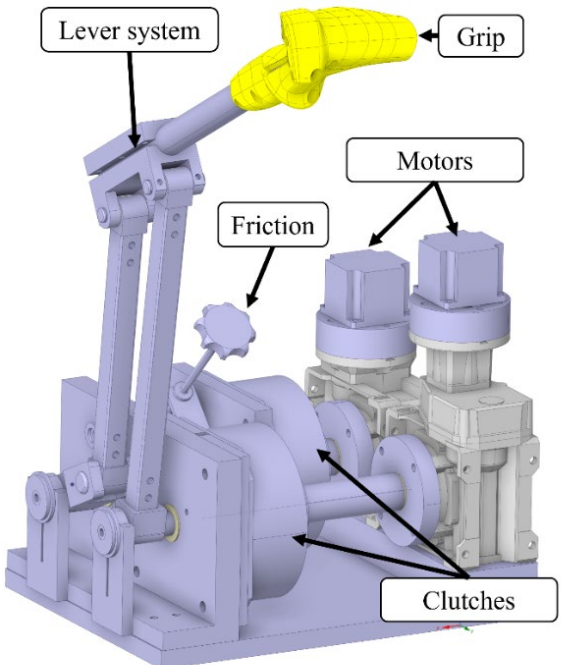

Figure 13: CATL prototype front view

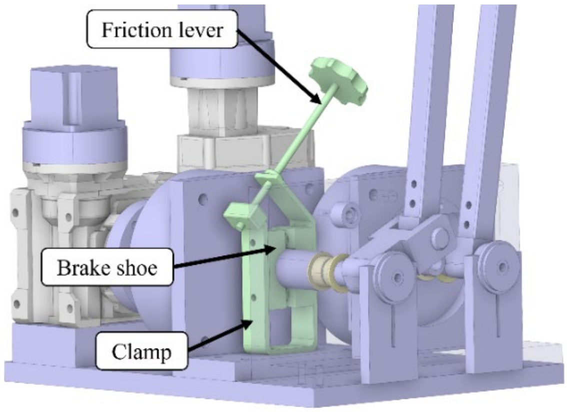

Figure 14: CATL prototype side view

Grip design

As already discussed, Special care was taken in the development of the CATL grip. More requirements were added to the grip design with respect to the basic assumptions mentioned above (with reference to Figure 15):

- the grip can be operated with two different hand positions:
    - in helicopter mode the hand is aligned with the control lever (collective-like control)
    - in airplane mode the hand is perpendicular with respect to the control lever (throttle-like control)
- the pilot can switch between the two hand positions without releasing the grip
- the following controls are integrated into the handle and duplicated for both hand positions:
    - A thumbwheel for adjusting the nacelle angle
    - Two pushbuttons: a generic Kill-Switch and a Force Trim Release
    - A 4-way beep switch controlling Collective and Yaw Trim.

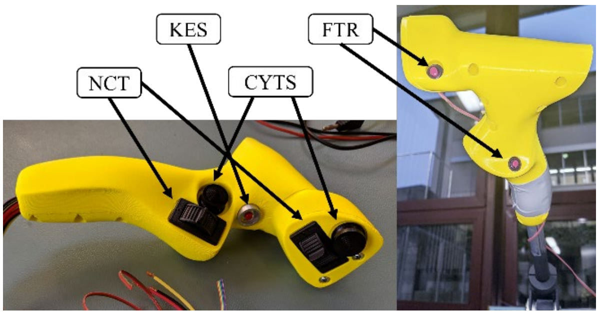

Figure 15: CATL grip equipped with switches: view from the side (left) and from the bottom (right).

The best compromise was to have a double set of switches placed for the helicopter and airplane modes. This allows the pilot to easily reach all the switches without any effort. To support XV15's basic functionalities, four switches have been selected:

- Nacelle Control Thumbwheel (NCT): these are thumbwheels with two positions (Forward and Aft) plus a central detent. When the thumbwheel is in the center detent position there is no command to the nacelles. When the thumbwheel is pressed Forward or Aft the nacelles are commanded in the forward or backward direction therefore providing an intuitive nacelles control to the pilot
- Force Trim Release (FTR): push button that forces the clutch (one of the existing two depending on the mode in which the aircraft is flown) to open. Therefore, the corresponding command anchor point (collective or throttle) is removed
- Kill Emergency Switch (KES): provision pushbutton to be used in case of emergency to reconfigure the functionalities of the CATL or to stop a specific function performed by the CATL; the KES is currently not used
- Collective and Yaw Trim Switch (CYTS): 4-way switch that, when pressed in a specific direction, produces a trim command in that direction. 4 directions are possible: Collective up and down, Yaw trim command left and right. When the switch is released, it returns to the center where no command is generated.

Electronics and Software design

The position sensors and the switches outputs are acquired by Programmable Logic Controllers (PLC) that also take care of the control of the CATL motors and clutches.

The CATL software was structured in such a way that the unit can be operated both manually and automatically by the FCS related functionalities. The communication between the CATL and the ReDSim real-time simulation computer is implemented via a UDP interface.

A detailed description of the electronics and software design of the CATL can be found in [Lüthi et al. 2017].

4 Real-Time Simulation Setup

4.1 XV15 model

As pointed out by [Primatesta et al. 2023], in the literature, several tilt-rotor aircraft models have been proposed [Dreier et al. 2007][Dugan et al. 1980][Churchill et al. 1982][Harendra et al. 1973].

A quite comprehensive study has been presented in [Ferguson 1988], where the GTRS model initially presented in [Harendra et al. 1973] is enhanced. More recently, several works based on the GTRS have been published for the development of new mathematical models [Padfield 2018][Kleinhesselink 2007][McVicar 1993].

In [Barra et al. 2019] the XV15 GTRS Matlab-Simulink® based mathematical model has been revised and improved for real-time simulation. A novel gimballed rotor mathematical model has been later introduced in [Abà et al. 2020]. Based on these studies, a tilt-rotor simulation model has been implemented in the ZHAW ReDSim Real-Time simulator [Barra 2022]. Additionally, a more convenient and portable version of the simulation environment has been created based on a portable workstation to be used by students and researchers without requiring specific and expensive hardware [Primatesta et al. 2022][Primatesta et al. 2023].

As already mentioned, the in-house developed XV15 model has been equipped with a set of dedicated flight control laws [Bernhardsgrütter et al. 2020] [Briamonte 2022]. These have been further improved and integrated with the CATL with the additional objective of providing a fail-safe scenario for possible / plausible failure conditions. The adopted control strategy will be presented in paragraph 4.3.

The model has been equipped with an actuation system the characteristics of which are shown in Table 1. While the model is fully nonlinear, only a few nonlinearities have been introduced for the time being. No loading effect has been considered so far.

Actuator	Dynamics	Bandwidth	Rate Capability
Flaps	1/s	N/A	4 deg/s
Swashplate Servos	1st Order	5 Hz	Unlimited
Nacelles	1st Order	1 Hz	Between 2 and 8 deg/s (Position dependent)
Ailerons	1st Order	5 Hz	Unlimited
Elevator	1st Order	5 Hz	Unlimited
Rudders	1st Order	5 Hz	Unlimited

Table 1 – XV15 Model Actuation System

Attitudes, rates, accelerations, altitude and airspeed sensors have been represented by generic 8Hz 1st order filters. These will be soon replaced by a sensor suite compliant with industrial standards such as the ARINC ones [ARINC705] [ARINC706] [ARINC707]. At the present time, this is not considered to be the focus of the work.

4.2 XV15 Conversion Corridor and Procedure

During conversion, the pilot must stay inside the XV15 conversion corridor depicted in red in Figure 16.

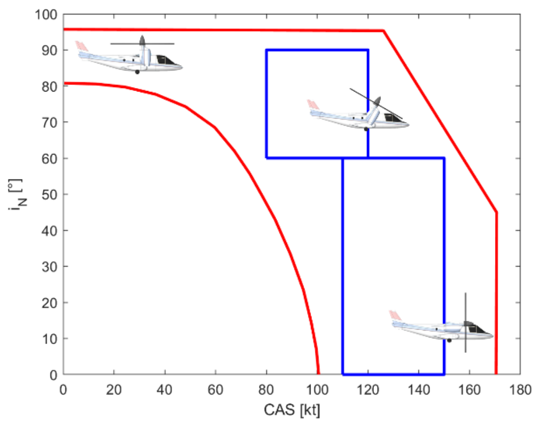

Figure 16: XV15 conversion corridor.

A simple procedure has been defined to help the pilot to perform this maneuver. The two blue rectangles highlight the simple procedure that the pilot can follow to convert from helicopter (HC) to airplane (AP) and vice-versa.

From HC to AP mode:

1. Accelerate to 80 KIAS
2. Rotate nacelles angle from 90° to 60° while maintaining a speed between 80 and 120 KIAS
3. stabilize the aircraft at 140 KIAS
4. rotate nacelles angle from 60° to 0° while maintaining a speed between 120 and 160 KIAS
5. Change rotors angular speed from 589 to 517 RPM

From AP to HC mode:

1. Decelerate to 150 KIAS
2. Change rotors angular speed from 517 to 589 RPM
3. Rotate nacelles angle from 0° to 60° while maintaining a speed between 110 and 150 KIAS
4. Stabilize the aircraft to 100 KIAS
5. Rotate nacelles angle from 60° to 90° while maintaining a speed below 80 and 120 KIAS

4.3 Flight Control Laws

A simple but effective set of Control Laws (CLAWS) have been implemented on the XV15 model [Bernhardsgrütter et al. 2020] [Briamonte 2022].

The inceptor configuration coupled with these CLAWS is summarized in Table 2.

Inceptor	Description
Cyclic Roll	Unique Trim Center Stick with constant gradient and damping
Cyclic Pitch	Unique Trim Center Stick with constant gradient and damping
Pedals	Unique Trim Center Pedals with constant gradient and damping
CATL - Collective	When in HC Mode the CATL provides a classical Collective with no gradient and friction
CATL - Throttle	When in AP Mode the CATL provides a classical Throttle with no gradient and friction

Table 2 – Inceptor configuration

The XV15 model has been fitted with a 3-axes (Roll, Pitch and Yaw) full authority Command Augmentation System (CAS) plus a limited authority Stability Augmentation System (SAS).

The pitch and roll axes CLAWS are classical Rate Command and Attitude Hold realized with PI controller having gain scheduled with airspeed.

Above 40 kt (with some hysteresis to prevent continuous mode switching) a Turn Coordination logic is activated. In Turn Coordination the Yaw axis CLAWS is a PI Ny command system with gains scheduled with respect to airspeed. When Turn Coordination is not active the Yaw axis CLAWS is a PI Rate Command System.

Limited authority SAS on roll, pitch and yaw axes with gains scheduled with respect to airspeed and nacelles angle can be activated or deactivated by a cockpit switch.

Even if a collective governor as described in [Ferguson 1988] is currently implemented in the XV15 model, it was decided to carry out the first assessment of the CATL using a sort of ideal engine that will always keep the rotors RPM at the desired value.

The CLAWS commands are the sum of the CAS and SAS system demands. These commands are then converted into Swashplate and surface desired position by means of a mixing unit defined as per [Ferguson 1988] (see Figure 17).

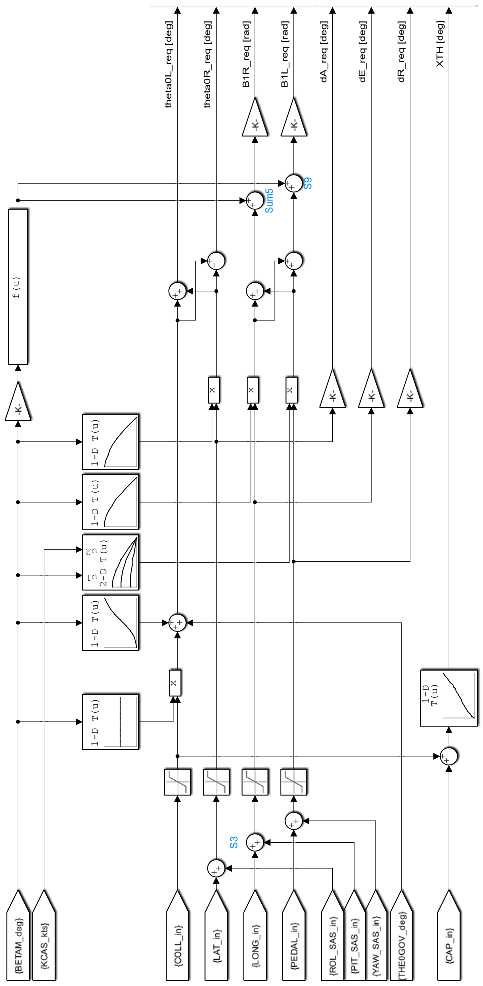

Figure 17: XV15 Mixing Unit

To reduce pilot workload during the conversion, the deflection of the flaps was automatically scheduled with indicated airspeed (see Figure 18). This approach is, of course, not in line with the XV15 and must be validated. Nevertheless, it was considered acceptable for this preliminary set of tests.

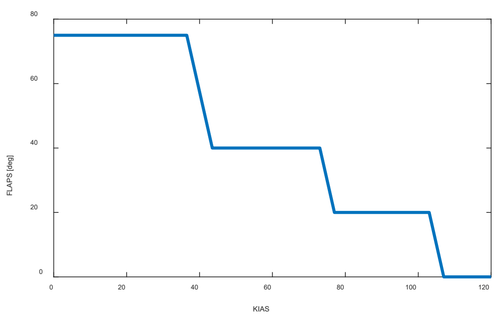

Figure 18: Autoflap Function Schedule

4.4 CATL Functionalities

As described in the previous section, the tiltrotor inputs come from the stick, pedals and CATL. At a nacelle angle $i_N = 90°$, i.e. in helicopter mode, the pilot must pull the collective as usual and once she/he stabilizes the prescribed airspeed, she/he can start the conversion procedure. On the other hand, when flying in airplane mode ($i_N = 0°$), the pilot can use the CATL as a normal throttle lever. The novelty lies in the pilot actions during the transition phase, while the operational limitations remain unchanged as depicted in Figure 16.

The current CATL uses a hysteresis for the selection of lever motion and command during the conversion phase. Figure 19 shows the Collective in Command Logic: when this is true, the collective is in command (HC mode see Figure 9). For $i_N > 55°$, the collective motion and related command remain active. On the other hand, when we are converting from airplane to helicopter mode, the pilot must use the thrust lever. For Nacelle angle $i_N < 65°$, the throttle motion and related command remain active.

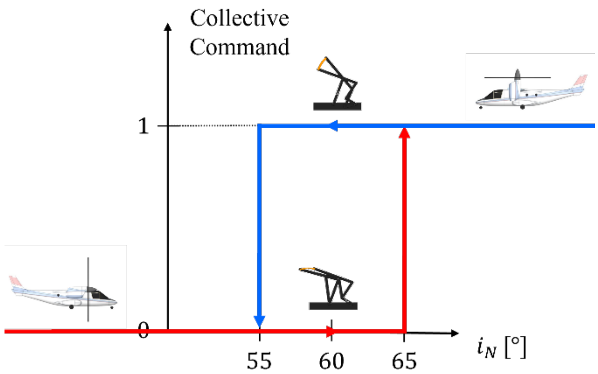

Figure 19: CATL hysteresis logic.

The nacelle angle is commanded by the NCT switch (see Figure 15). Three predefined positions are defined for the nacelles:

1. 90° ➔ Nacelles in HC Mode
2. 60° ➔ Transition from HC to AP Mode or vice-versa
3. 0° ➔ Nacelles in AP Mode

Pressing the thumbwheel in one direction will cause the nacelles to go to the next predefined position. For example, pressing the thumbwheel forward once while the nacelles are at 90° will cause the nacelles to go to 60°. Therefore, there is no need for the pilot to have precise control of the nacelles position via the thumbwheel. To prevent inadvertent nacelle activation, the thumbwheel signal is first “debounced” by an appropriate logic.

The conversion procedure remains similar: after the takeoff and having reached a speed between 80-120 kts in forward flight, the pilot can tilt the nacelles with the NCT switch. Once the aircraft is stabilized at $i_N = 60°$, the pilot can control the speed always with the collective lever. Later he can complete the full transition by using again the NCT switch by rotating the nacelle to airplane mode.

The opposite conversion, from airplane to helicopter, corresponds to the same procedure, apart from the lever in command at $i_N = 60°$. As explained before, here the thrust lever will be used.

The transition from one mode of operation to the other shall be marked by several events such as aural and visual cues. In the CATL, this transition is also marked by the mechanical transient of one clutch engaging and the other disengaging. This provides a very effective tactile and aural cue to the pilot. Currently, this mechanical cue is so effective that no aural or visual cues have been implemented in the simulator.

The complete CATL logic is presented in Figure 20. In practice, the CATL motors receive only speed commands. Based on these the position loops are realized. The loop closures (one per motor) of the position loops are realized by means of nonlinear gain tables to cope with motor nonlinearities.

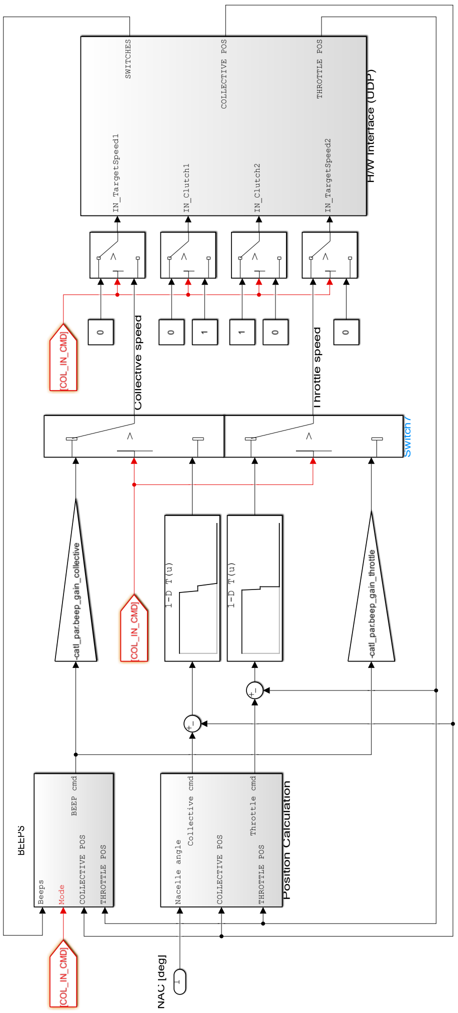

Figure 20: CATL logic

The CATL has been designed to support both hands-on and hands-off operations. The focus of this work lies on the hands-on part. In hands-off operation, both clutches are closed, and the motors are commanded by FCS Autopilot functions. The pilot can interact with the CATL via CYTS (beeps) and is always able to override the Autopilot commands using the Force Trim Release (FTR) push buttons. The FTR will release the clutch of the channel in command (collective or throttle) and stop the Autopilot commands to the related motor. Additional features, such as detection of pilot hands-on via current monitors or out of detent switches can be added to the CATL.

A specific approach has been implemented for managing the two motions (collective and throttle). In HC mode, the thrust joint remains stationary at its midpoint position, while in AP mode, the collective joint remains fixed at its midpoint position. During the transition from HC to AP, the collective position needs to smoothly move from its current value to the middle position. Vice-versa, during the transition from AP to HC mode, the throttle will gradually transition from its current position to the middle position. This strategy ensures a safe operational scenario in case of failure(s) during the transition process. As a result, when transitioning between HC and AP modes, the motors should generate the necessary motion of the lever as indicated by the distinct power lines shown in Figure 21.

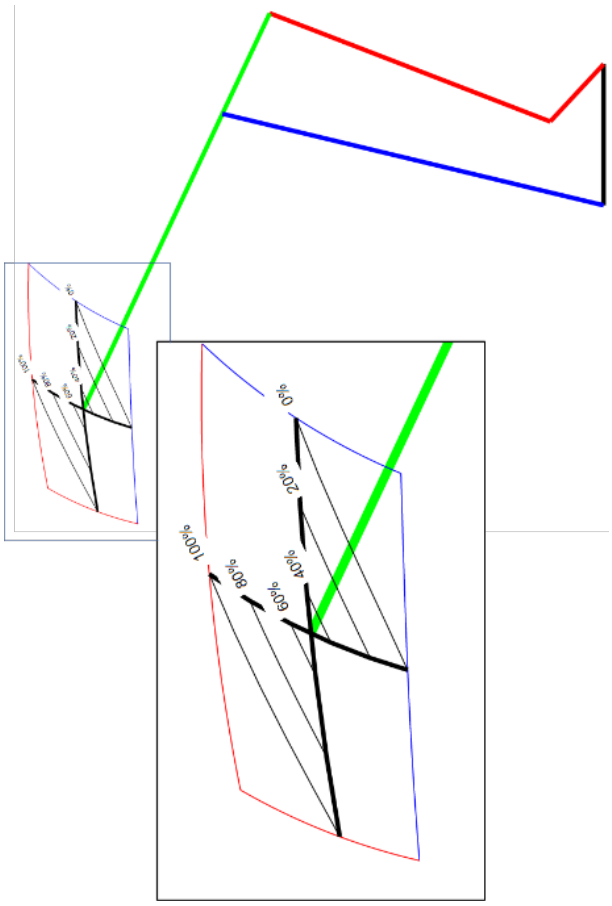

Figure 21: CATL Position Envelope

Following the integration of the CATL into the ReDSim Simulator of the ZHAW (see Figure 22), a series of tests have been performed to define the appropriate friction levels for hands-on operation as well as appropriate speed tables for motor commands.

With reference to Figure 22, the existing speed brakes lever was used to command the rotor RPM. The lever position to RPM command table (see Figure 23) is designed to provide an intuitive interface to the pilot.

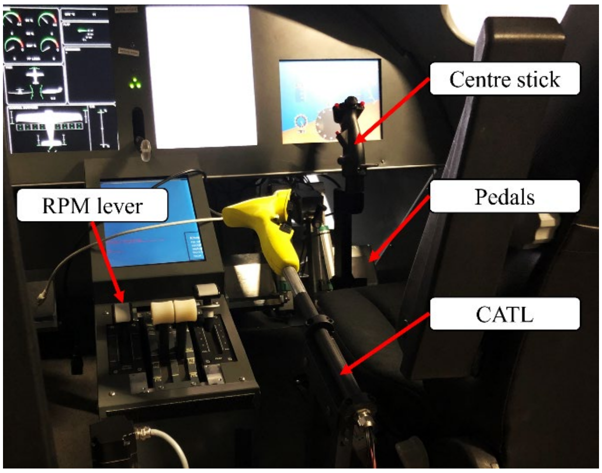

Figure 22: CATL Installation into the ReDSim

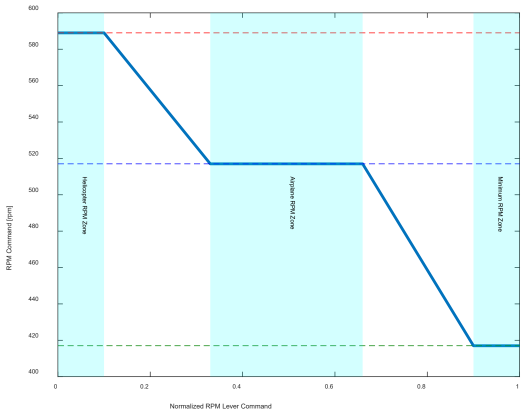

Figure 23: RPM Lever to Commanded RPM Mapping

The RPM command is further rate-limited to 40 RPM/sec to prevent rapid rpm changes.

5 Preliminary testing

The CATL is the result of several years of intense activity. A thorough test of this device requires the involvement of several stakeholders such as experts from industry and academia as well as test pilots.

Nevertheless, a preliminary test of the unit can be carried out with the following objectives:

<u>OBJ#1: Preliminary Verification of Design</u>

Verify that design requirements have been correctly implemented in the prototype. In particular, with respect to: Feel system characteristics (friction, motor speeds, freeplay, etc.), Switches and associated logics (beep control, thumbwheels and nacelles command logic, autoflaps, etc.), Display information, etc.

<u>OBJ#2: Preliminary Validation of Design</u>

Preliminary evaluation that the current solution is the complete and correct one. An expected outcome of this task is also to identify weaknesses and areas of improvement in the design.

One of the key points for the preliminary testing was the separate assessment of Handling Qualities (HQ) from Workload. In fact, the different mission task elements (MTE) for HC and AP modes are not necessarily characterized by similar workloads and, therefore, cannot be really compared.

Another important point to be mentioned is what the preliminary test is **<u>not</u>** supposed to assess. Among the aspects, that were not considered part of the assessment, the most notable one is the CLAWS effectiveness and functionalities. It has been assumed that they are sufficiently representative for the given tasks.

Most tilt-rotors / convertiplanes cannot perform landing in AP configuration. This is the case for XV15 which cannot land in AP mode in normal conditions. Nevertheless, to allow a comparison of HC and AP MTEs with similar workload levels, the model of the XV15 has been modified to allow this. Clearly, these modifications are meaningful only for the purpose of this work and, therefore, shall be considered with due caution. However, this scenario can be representative of an emergency landing for the XV15.

5.1 Test Setup

The tests were performed in the ZHAW in-house-built research flight simulator ReDSim (see Figure 24). This is a fixed-base simulator used for didactics and research purposes. It had its maiden flight in 2011. The mechanical design and most of the software components were realized by professionals from the ZHAW Centre for Aviation, along with students from various degree programs.

Figure 24: The ReDSim from the back

The ReDSim is primarily utilized for instructional courses and serves as a laboratory facility for external partners from diverse fields. The ZHAW Center for Aviation also employs the ReDSim in Human-Machine Interaction research.

The ReDSim can simulate a wide range of aircraft configurations, ranging from gliders to business jets, helicopters, and even tiltrotor aircraft. It offers the ability to test different aircraft setups in a virtual environment, making it an invaluable tool for aircraft design.

Featuring a professional Control Loading System (CLS), the ReDSim can simulate the complete control chain, from aerodynamic moments on control surfaces to the mechanical characteristics of the aircraft control system.

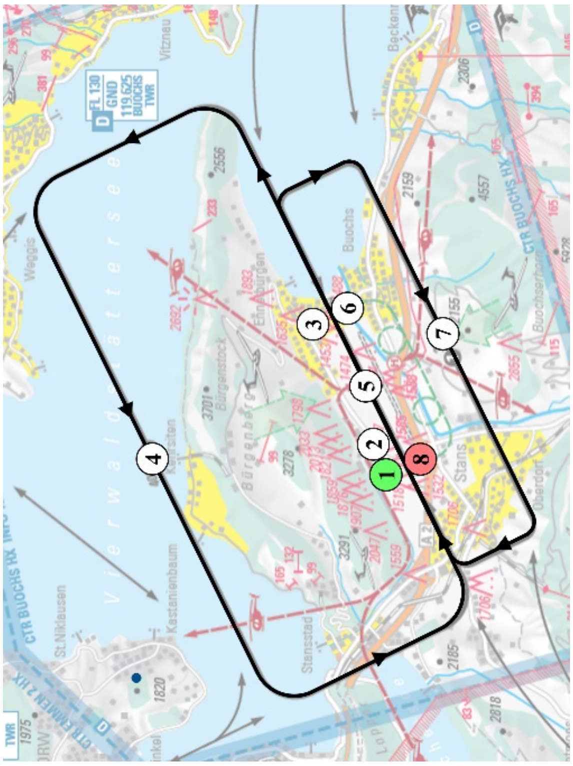

Figure 25: Buochs Airfield VAC and test points

The ReDSim generic cockpit provides a standardized environment that does not represent a specific aircraft type but can be configured to meet specific user requirements. The visual system provides a 180° field of view with auto-calibration features. The simulator also incorporates an audio system.

Three tests were performed with the described XV15 model with SCAS (SAS + CAS) active. Transitions from HC to AP mode and back were carried out for each test. The chosen location was Buochs Airfield (LSZC), Switzerland (see the Visual Approach Chart (VAC) Figure 25). The adopted test sequence is summarized in Table 3.

#	Description	Phase Name
1	Takeoff in HC mode	Start of Test
2	Hover for ~30 seconds	Hover
3	Conversion HC to AP	HC ➔ AP
4	Circuit #2 VAC chart (large one in Figure 25)	Circ. #2
5	Approach, Touch-and-go in AP mode	Approach
6	Conversion AP to HC	AP ➔ HC
7	Circuit #1 VAC chart (small one in Figure 25)	Circ. #2
8	Landing in HC mode	End of Test

Table 3 – Test Sequence

After a test sequence was completed, the pilot was given the Cooper-Harper (see Figure 26) and Bedford (see Figure 27) rating scales, to assess HQ and workload, respectively. The pilot was then asked to rate specific aspects of the task.

The well-known Cooper-Harper rating scale was developed in the 1960s [Cooper et al. 1969]. Nowadays, it has still a crucial value in the development and certification of novel aircraft designs. This scale allows pilots to quantify their subjective evaluations of the different HQ characteristics of the aircraft.

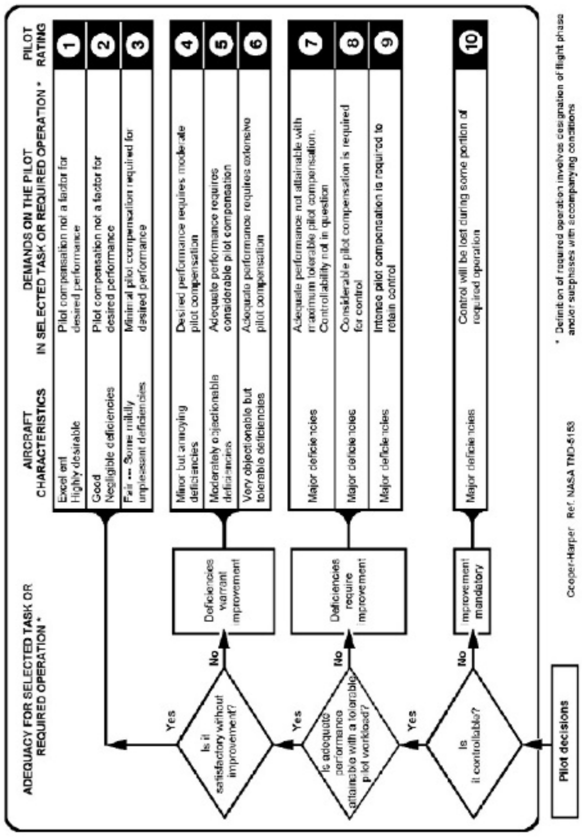

Figure 26: Cooper-Harper Handling Qualities Rating Scale

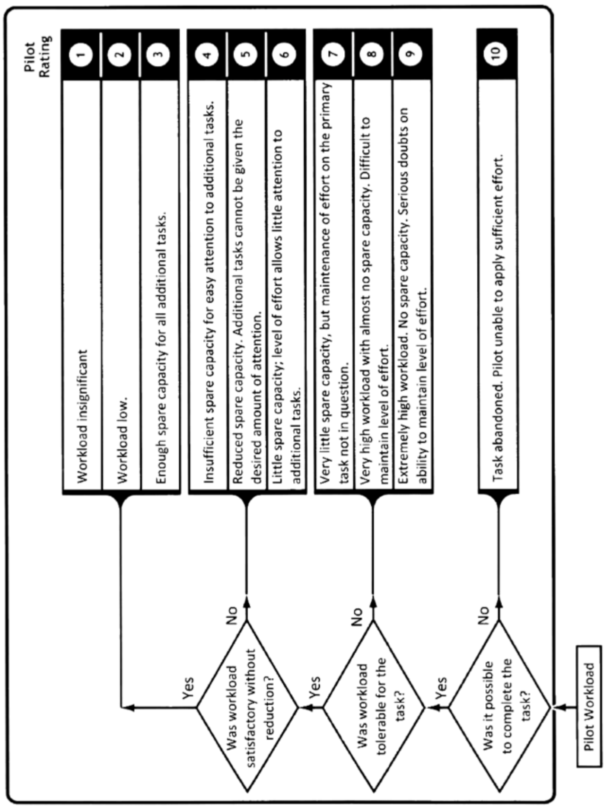

Figure 27: Bedford Workload Rating Scale

The Bedford rating scale, developed by Ellis and Roscoe, is used to assess the pilot's cognitive workload. The Bedford workload rating scale [AGARD 233] plays a vital role within our framework, particularly in designing human-machine interfaces and cockpit ergonomics. Workload rating scales are used to quantify the cognitive and physical demands placed on pilots in different operational scenarios. Similarly to the Cooper-Harper Rating Scale, its goal is to improve the safety of aircraft by analyzing the pilot workload and trying to reduce it.

The pilot was asked to give a rating on both scales with respect to the 4 control axes, i.e., roll, pitch, and yaw axes, and thrust, for the following mission task elements: hover, conversion from HC to AP mode, landing approach, and conversion from AP to HC mode.

5.2 Test Execution

Several piloted tests were performed during the development of the CATL. This allowed several fixed and rotary wing pilots to get more familiar with the CATL concept while gathering invaluable feedback for unit development. Unfortunately, none of these pilots had hands-on experience with convertiplanes.

For the CATL preliminary testing, a helicopter pilot with circa 1000 flight hours was selected. He had already flown the XV15 model in the simulator using classical collective and throttle inceptors and had also some experience with the CATL device.

Figure 28 and Figure 29 show the 2D and 3D aircraft trajectories, respectively, during a typical test.

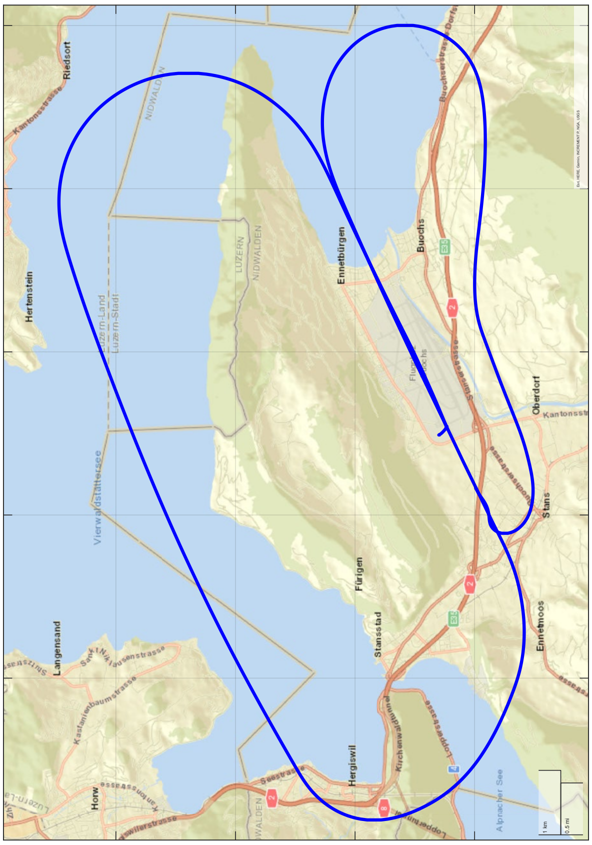

Figure 28: Test #3 - 2D Trajectory

Figure 29: Test #3 - 3D Trajectory

The pilot was allowed to have a first run to familiarize himself with the task and simulator setup. After an initial shakedown, he suggested having two different circuits for the test. A large one for the HC➔AP conversion and AP landing and a smaller one for the AP➔HC conversion and HC landing. These are the two standard circuits reported in the VAC of the Buochs Airfield (see Figure 25) and correspond to aircraft up to 5.7 tons of MTOM (small circuit) and aircraft over 5.7 tons MOTM (large one).

5.3 Results

At the beginning of the test, the pilot had to go through a learning curve, his initial comment was "*the task is rather complicated*". As the different tasks were repeated, he got more familiar with the test sequence. Yet, it is fair to say that the conversion task is a demanding one. During conversion, the pilot must control speed, attitude, altitude and nacelle angle. In the tested solution, the pilot does that by means of three interfaces: longitudinal cyclic, CATL and thumbwheel switch.

During the first AP➔HC conversion, the pilot tried to still use the collective instead of the throttle but soon realized this and corrected himself.

Figure 30 shows the conversion corridor and procedure limits with respect to the flown patterns. Each test is represented by a colored line split into two parts. The first part (continuous line) represents the initial portion of the test, from take-off in HC mode to Approach in AP mode. Thus, this part contains the HC➔AP conversion. The second part (dashed line) represents the final portion of the test, from Approach in AP mode to landing in HC mode. Thus, this part contains the AP➔HC conversion.

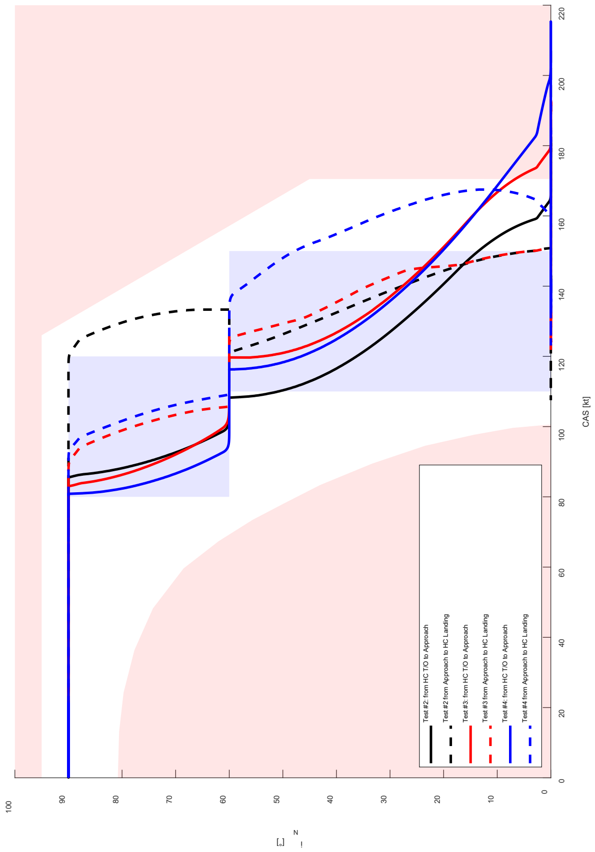

Figure 30: Respect of Conversion Corridor and Procedure

Figure 30 shows how demanding it is for the pilot to remain inside the given boundaries. Despite the given reduced limits of the conversion procedure, the pilot overshoots the conversion corridor during the HC➔AP conversion when the nacelle angle is close to 0°.

With reference to Figure 30, also evident is the difficulty in staying inside the procedure boundaries during the AP➔HC conversion.

As already discussed, the evaluation of the CLAWS was not part of the preliminary test, nevertheless, the pilot comments seem to confirm that the chosen CLAWS strategy was appropriate for the purpose of the test.

The average HQ and workload ratings are reported in Figure 31 and Figure 32, respectively. With respect to these figures several remarks can be made.

As expected, differences exist between HQ and workload ratings. The Thrust Axis (ThAx) workload in Approach is considered low but the associated HQ ratings show that pilot compensation is required to achieve the desired performance. This can be explained by the non optimal behavior of the model in this scenario. As explained, the model was modified to allow landing in AP mode. It must be noted that no information is available on this emergency procedure for the XV15. One of the implemented modifications was to significantly reduce the RPM in Approach phase in order to reduce the approach speed. The resulting aircraft response to ThAx changes in this case (throttle) is definitely not optimal and rather abrupt.

Also interesting is that, from the lateral directional point of view, the HC➔AP conversion seems to be associated with a higher workload than the AP➔HC one. This can be related to a known deficiency in the response of the aircraft model around 80-90 kts for high power settings. This problem was investigated in the past and requires further validation of the model.

The ThAx workload in AP➔HC conversion is higher in comparison to the HC➔AP one. One explanation can be that the pilot is a helicopter pilot. On the other side, the reduction of the speed via the ThAx and the associated pitch control seems to be more workload intensive in the AP➔HC conversion.

Even if the pitch axis was not the focus of this investigation, it is evident from the results that longitudinal control needs special attention during conversion as indicated by both HQs and Workload ratings. In practice, pitch control in transitions (both HC➔AP and AP➔HC) is critical. This calls for a critical review and redesign of the pitch CLAWS during conversion.

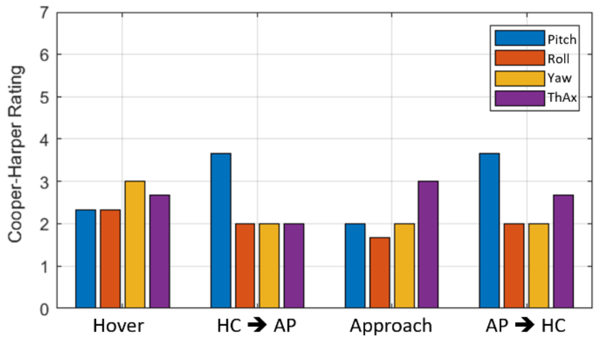

Figure 31: Cooper-Harper Rating

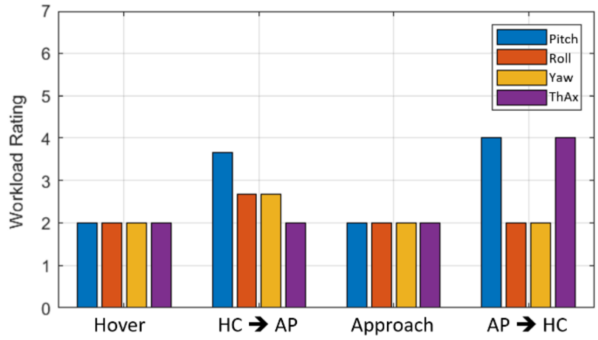

Figure 32: Workload Rating

6 Conclusion & Outlook

By providing "natural" interfaces to the pilot such as throttle and collective, the CATL cannot be less effective than one of these two solutions during flight in HC or AP mode.

One interesting result of the tests is also that the workload associated with AP tasks is not necessarily lower than the one of HC tasks. The tests show that if the flight control system functionalities and thrust response are not optimal, the thrust axis workload in AP mode can be as high as that in HC mode.

The real question is if the CATL is more effective during the conversion phase, while the thrust axis moves with the nacelle angle.

Unfortunately, conversion is a highly demanding task that requires special care at both inceptors and augmentation levels. On one end, this justifies the current work and attention given to the inceptor. On the other end, this urges for stronger integration of the flight control laws and inceptor functionalities. These two aspects cannot be really developed separately.

As a matter of fact, the whole assessment of the CATL is strongly affected by this issue. During the conversion tests, the pilot was kind of task saturated. It is evident that the pilot assessment of the CATL was always biased by the high workload.

One way to cope with this issue is to involve pilots that have flown tilt rotors. The authors will definitely try this approach in the future. On the other hand, a more effective set of integrated thrust and pitch control laws shall be developed to automate some of the tasks that the pilot needs to perform during conversion, such as attitude, speed and nacelle control.

Based on the above considerations, the results of the preliminary tests encourage the investigators to proceed further with the CATL concept. Various good features have been recognized such as intuitive commands, clear transition between modes and simple integration with current control systems.

Nonetheless, several areas of improvement have been identified. At the top of the list is, for sure, the already-mentioned control strategy. Once this issue has been addressed, other aspects can be improved.

For example, the nacelle angle of 60° has been used as the transition point between HC and AP modes. This is not necessarily the optimal value. More investigation on this is required. Moreover, the control strategy can be augmented / improved by a hands-on detection logic. This logic can also be used to provide additional envelope protection features.

Finally, several XV15 model modifications have been identified that must be implemented into the simulation model for a more effective and realistic testing of the CATL.

7 Acknowledgements

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