Evaluation of Simulator Cueing Fidelity for Rotorcraft Certification by Simulation

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ABSTRACT

Before their entry into service, newly developed rotorcraft must go through an extensive certification process in order to receive a type certificate from the certification authority. A vital and long-lasting phase of this process is the compliance demonstration. This phase involves a large amount of flight testing, which leads to high expenses for the rotorcraft manufacturer and can be considered as high-risk when it comes to rotorcraft safety, especially for scenarios including control system or engine failures, as in the case of a category-A rejected take-off (CAT-A RTO). The Rotorcraft Certification by Simulation (RoCS) CleanSky2 research project aims to reduce the amount of flight testing required for compliance demonstration by using flight simulation, to achieve an increase in safety (less hazardous situations) and effectiveness, and a reduction in certification duration and costs. Within the project, pilot-in-the-loop simulator test campaigns were conducted at DLR and NLR, investigating the visual cueing fidelity required for performing a CAT-A RTO scenario. Emphasis was put on varying the available field of view (FoV) for the pilot and investigating the suitability of virtual reality (VR) devices. Subjective and objective results from these simulator campaigns, as well as pilot comments are presented in this paper.

INTRODUCTION

The capability of using flight simulation in lieu of high-risk compliance demonstration flight testing was already shown by Leonardo Helicopters (LH) in the past years. In 2016, the simulation of an AW189 power-off landing manoeuvre provided an essential contribution to the certification process (Ref. 1). In 2017, AW169 tail rotor failures were tested in a fixed-base simulator at LH facilities. Evidence was provided to the certification authority that the rotorcraft could be safely recovered and landed after failure (Ref. 2). Despite the technical possibilities of using simulators for certification nowadays, certification guidance material only exists for simulators used for training (Ref. 3) and not for aircraft certification purposes.

Therefore, the goal of RoCS is to consolidate a set of guidelines, agreed with the certification authority, for the flight simulation model and simulator cueing systems to be used for future rotorcraft certification in order to replace or reduce the number of flight tests. These guidelines will be based on minimum requirements for future certification simulators in order to maximize the cost-benefit from using simulation instead of flight tests. The flight simulation guidelines will be, in part, an outcome of pilot-in-the-loop simulator campaigns performed at project partner facilities. This paper presents the objective as well as subjective pilot assessment results of a first set of simulator cueing fidelity tests specific for certification tasks selected within the project. Project work focuses on a selection of candidate paragraphs from the European Union Aviation Safety Agency's (EASA) "Certification Specifications and Acceptable Means of Compliance for Large Rotorcraft (CS-29)" (Ref. 4). The paragraphs have been selected by considering and weighting 'simulation feasibility', 'flight test risk reduction' and 'overall compliance demonstration cost reduction'. For this paper, emphasis was put on evaluating visual cues for a CAT-A RTO scenario in a confined area.

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EXPERIMENTAL SETUP

Pilot-in-the-loop simulator studies are being performed in project partners' simulator facilities which differ in their specifications. To take full advantage of the available facilities, the experiments at the DLR facility focus on field of view limitations, whereas the experiments at the NLR facility focus on the use of VR devices as visual system. The following sections give a detailed description of the experimental setup.

Simulation Facilities

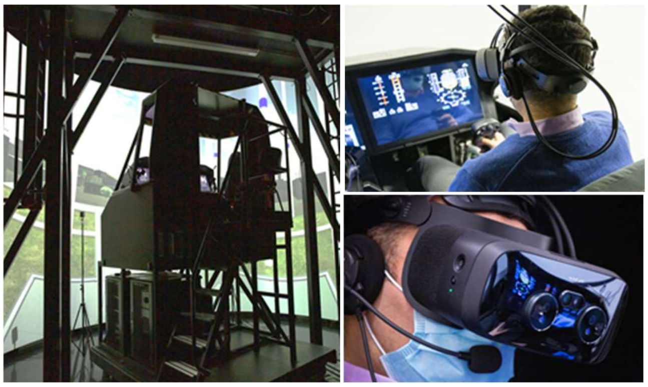
The simulator cueing fidelity test campaigns discussed in this research were conducted in the Air Vehicle Simulator (AVES) at the German Aerospace Center (DLR) and the Helicopter Pilot Station (HPS) at the Royal Netherlands Aerospace Center (NLR).

The full flight simulator AVES (see Figure 1) features a cockpit that represents DLR's Active Control Technology/ Flying Helicopter Simulator (ACT/FHS) which is a highly modified version of the EC135. A large projection dome and 15 LED projectors enable a 240° x 93° (+35°/-58°) Field of View (FoV) from the pilot seat. The simulator can either be operated as a fixed-base simulator or as a six degrees of freedom motion simulator (Ref. 5).

Figure 1. AVES from the outside and inside at DLR

The HPS (see Figure 2) is a generic fixed-base rotorcraft simulator that can be customized to represent a multitude of helicopter types in terms of flight model and the representation of flight instruments. The outside world can be represented by either a visual projection system (a), which has a maximum FoV of 190° x 80° (+35°/-45°) from the pilot seat, or through the use of VR (b).

For simulator test campaigns within the project, an AW109 Trekker FLIGHTLAB model has been provided by LH. Unlike NLR, DLR does not have access to FLIGHTLAB. Therefore, a stitched model was generated which is based upon linearized point models that have been extracted from the nonlinear AW109 FLIGHTLAB model. The stitched model aims to ensure that it is suitable for tests conducted within the required operating range for scenarios to be tested in simulation.



(a) (b)

Figure 2. HPS with activated projection screen (a) and VR device (b) at NLR

Flight task

For cueing fidelity assessment, a CAT-A RTO has been performed by the test pilots in both simulator facilities. This scenario, amongst others, was selected as a suitable candidate to show whether and how simulation could be used as a means of compliance for airworthiness specification requirements related to rotorcraft flight aspects. The CS-29 candidate selection in RoCS is based upon the criteria 'simulation feasibility', 'flight test risk reduction', and 'demonstration cost reduction'. A detailed description of the criteria and the scoring process that led to the selection has been published in (Ref. 6).

During the compliance demonstration phase, it has to be shown to the certification authority that an RTO can safely be performed after a single-engine failure during the take-off and landing phases. The rejected take-off is especially critical when performed in confined areas.

Therefore, it was decided to utilize a confined take-off and landing area for simulating the RTO scenario. According to FAA's Helicopter Flying Handbook (Ref. 7), a confined area is described as "an area where the flight of the helicopter is limited in some direction by the terrain or the presence of obstructions, natural or manmade". Such a confined area was replicated in the partners' simulators for cueing test campaigns.

The pilots who participated in the tests were asked to start the manoeuvre by taking off as described in the AW109 flight manual, starting from a 3 ft hover at the centre of the helipad. The stable hover position is followed by a climb while maintaining a 4-5 kts backwards groundspeed (GS) and 300-400 fpm rate of climb (ROC) until reaching a prescribed take-off decision point (TDP) height.

Reaching the TDP, the pilot needs to decide whether to reject or continue the take-off. If an engine failure is identified after exceeding TDP height, a continued take-off (CTO) must be performed. The rejected and continued flight paths of a back-up take-off manoeuvre are illustrated in Figure 3.

In the case of the RoCS campaigns, an engine failure was simulated prior to reaching TDP. Therefore, the pilot was told to react to the failure, reject the take-off, intersect the take-off flight path after losing height, and return to take-off position in a controlled manner. During the whole manoeuvre, the pilot should endeavour to maintain sight of the helipad. The RTO procedure was repeated multiple times under various conditions and TDP heights. The AW109 has prescribed TDP limits of 70 to 400 ft, depending on the environment (buildings, trees, etc.).

A numeric GS indicator on the main instrument panel was provided to the pilot in both simulators for maintaining the backwards GS target value. In combination with the vertical speed indicator, a head-down climb gradient cue could be obtained. This was an attempt to compensate for the lack of chin windows in NLR's simulator while using the projection system, which arguably affected the scanning pattern of the pilot considerably.

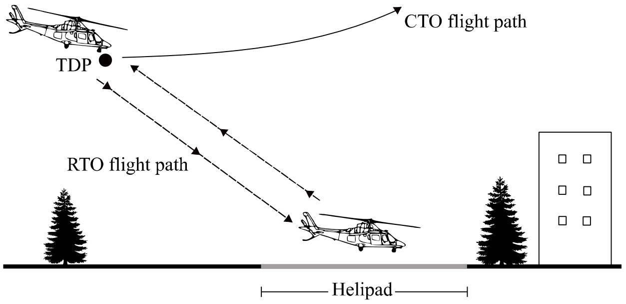


Figure 3. AW109 take-off profile in confined area

DLR visual cueing setup

One of the main flight simulator features is visual cueing. The fidelity of outside the window visual cues affect pilots' perception and their ability to fly the aircraft. Especially for helicopter operations close to the ground, good visual cues are important. The pilot needs to be able to assess the aircraft sink rate and helicopter altitude during descent and landing. References in the near and far environment are used for orientation and assessment. These can be ground markers, buildings or other simulated objects. In order to ensure that the pilot is able to use these references, adequate FoV has to be provided. When the FoV is limited to a certain extent, references used by the pilot can be lost, requiring adaptation of the control strategy (if possible).

Guidance material for visual cueing fidelity only exists for flight simulators used for training (Ref. 3) and not for certification purposes. Therefore, within the RoCS project, it was investigated how much FoV is required to adequately perform the selected certification flight test scenarios in a simulator.

For the simulator campaign at DLR, three different FoV-settings have been implemented in AVES. The AVES default FoV serves as a reference. All four FoV-settings are listed in Table 1 with their respective values for horizontal and vertical FoV angles. The horizontal value is equally divided between the left and right view. The vertical value is roughly divided by one third for up-view and by two-thirds for the down-view, in accordance with ICAO 9625 (Ref. 8).

Table 1. FoV-settings in AVES at DLR

Setting	Horizontal FoV	Vertical FoV (up/down)
AVES	240°	93° (+35°/-58°)
RoCS Sim	220°	78° (+20°/-58°)
FFS Level D	180°	60° (+24°/-36°)
FFS Level C	150°	40° (+13°/-27°)

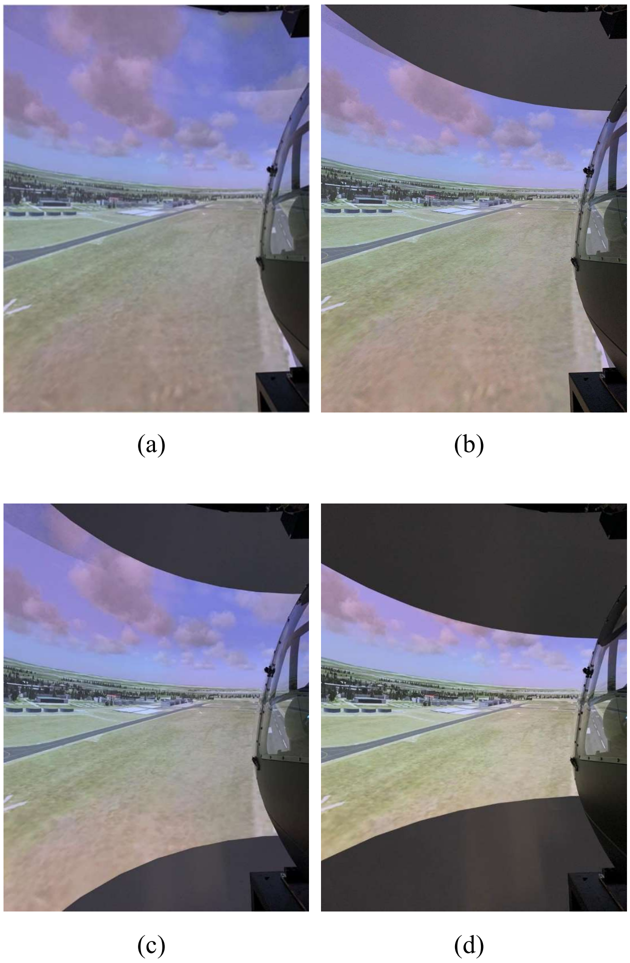


Figure 4. FoV Settings – (a) AVES, (b) RoCS Sim, (c) FFS Level D, (d) FFS Level C

The setting 'RoCS Sim' represents the FoV of the engineering simulator that is being built within the RoCS project. It has a similar horizontal viewing angle as the AVES. The vertical down-view is identical to AVES, as opposed to the vertical up-view which is limited to +20°. This enables an investigation of the relevance of vertical up-view FoV for an

RTO manoeuvre. The settings 'FFS Level D' and 'FFS Level C' represent the minimum FoV requirement for a full flight simulator (FFS) level D and level C, respectively, according to CSFSTD(H) (Ref. 3). Figure 4 shows the FoV limitations in AVES as generated by the visual system according to the different settings. Note that the pictures do not capture the horizontal limitation.

NLR visual cueing setup

Usage of standard projectors to visualize the environment inherently results in limitations of the Field of Regard (FoR) of the pilot. The FoR reflects the total observable area of the pilot, which is limited by the dome or cylindrical projection screen. For projection systems the FoR is equal to the FoV. VR devices do not have this constraint as the pilot is commonly capable of looking entirely around. These devices, therefore, offer an unlimited FoR. The unlimited FoR is one of the main advantages of VR over widely used projection systems. The other advantages include the lack of a necessity for a large and costly projection installation and improved depth perception due to stereoscopic vision. Unlike the FoR, the FoV determines the view which is covered by the visual system at a specific moment. A larger FoV typically increases the level of immersiveness and is, therefore, a prominent technical specification of VR devices (Ref. 9) (Ref. 10).

Two different VR devices, the Varjo XR-3 and the Pimax 8K-X (see Figure 5) have been used for the experiment (Ref. 11) (Ref. 12). Both VR glasses are considered state-of-the-art, either due to their high resolution (Varjo), or high FoV (Pimax). Due to technical and computational limitations, currently only a few VR devices exist which combine these characteristics. Nevertheless, in general, VR glasses demonstrate relatively high-resolution imaging, often available for economical prices compared to projection systems.

Figure 5. Varjo XR-3 (left) and Pimax 8k-X (right)

The specifications of the VR devices are listed in Table 2. The resolution is presented in Pixels Per Degree (PPD) as this takes both pixel count and FoV characteristics into account. The actual FoV values were determined at NLR in a test setup where FoV circles in VR are monitored by a camera placed at the human eye position (a.k.a. 'through the lens' photography). From the camera's images the number of visible circles is counted to determine the area which is viewed by the eye, i.e., the FoV. It should be mentioned that for both VR devices the FoV reflects an ellipse shape and not a rectangle, as the usage of terms such as horizontal, vertical, and diagonal FoV might suggest. Also, not all rendered pixels are visible to the user. Additionally, the outer areas of the Pimax' FoV appear rather 'blurry' due to the Fresnel lens, which could negatively affect the user's VR experience. During the experiment, the Pimax FoV software setting was set at normal (instead of the Pimax large, small, or so-called potato FoV setting). Although this had a major effect on the maximum FoV values, the normal setting was preferred as the alternative settings led to distortion of the visual perception, influencing the perceived visual cueing.

Table 2. VR devices specifications

	Varjo XR-3	Pimax 8k-X
Advertised FoV	115° horizontal	200° diagonal
Measured FoV	88° horizontal 65° vertical	140° horizontal 90° vertical
Lens Technology	Non-fresnel	Fresnel
Advertised Pixel count	Peripheral area 2880 x 2720 pixels per eye Focus area (27° x 27°) 1920 x 1920 pixels per eye	3840 x 2160 pixels per eye
Measured Resolution	Peripheral area 32 PPD Focus area (27° x 27°) 71 PPD	33 PPD

Assessment

In both simulator campaigns subjective assessments were obtained from the pilots, followed by an objective assessment using simulator data. As for subjective assessment, a metric was used that is based on the methodology to determine the useable cueing environment (UCE), presented in ADS-33 (Ref. 13) and illustrated in Figure 6. Besides assessing the cueing environment, the usage of this questionnaire contributes to the discussion between the pilot and other experiment attendees (e.g. the researcher, flight test engineer, and human factors specialist). The questionnaire protocol assists in identifying features which impact visual cueing qualities. This methodology was originally designed to assess cueing fidelity for handling qualities (HQ) flight testing. In principal, this method relates the quality of the visual environment to the required level of artificial stabilisation provided by a flight control system to achieve Level 1 HQs (Ref. 14). For pilots it is necessary to ensure that a sufficient level of cueing exists to complete a desired Mission Task Element (MTE). Pilots are required to award a visual cue rating (VCR) in pitch, roll, and yaw attitude and vertical and horizontal translational rate. VCRs are obtained by using a subjective pilot rating scale that ranges from a rating of one to five, where one is good, and five is poor. Average values of all participating pilots have been determined, resulting in five average VCRs. For each test case a minimum of three pilots must be used for the assessment. The two worst VCRs are extracted from the five average VCRs and plotted in the UCE chart in Figure 6 to determine the UCE. One among pitch, roll, and yaw attitude, and one between vertical and horizontal translational rate. A UCE of one equals a cueing environment where all the necessary visual information is provided to the pilot. A UCE of three indicates an inadequate visual cueing environment that does not allow the pilot to make aggressive inputs with confidence. The final UCE value is used to determine an aircraft response type required to perform the MTE under the given visual cueing conditions.

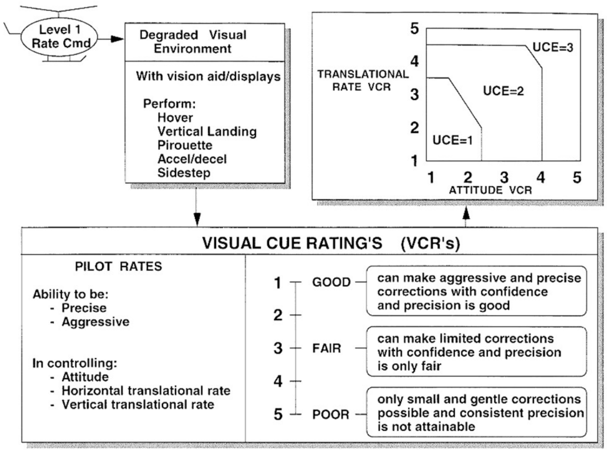


Figure 6. UCE methodology (Ref. 15)

As opposed to the ADS-33 methodology, the purpose of the simulator fidelity campaigns at DLR and NLR is to compare different visual cueing settings while flying a non-ADS-33 MTE. Therefore, the subjective assessment method used differs from the ADS-33 methodology in a way that no UCE value is being obtained and that the provided flight simulation model was not verified to be adequate for achieving Level 1 HQs. Besides that, the process of awarding VCRs has been inherited. For a better comparison, the VCRs of all visual cueing settings are illustrated in the novel chart shown in Figure 7. Attitude and translational rate VCR form a combined rating that falls under a specific area of the diagram. Areas are covered by different colours to indicate the visual fidelity based on VCRs. The colour definitions are as follows:

- Green: Good (1) to Somewhat good (2)
- Yellow: Somewhat good (2) to Fair (3)
- Orange: Fair (3) to Somewhat fair (4)
- Red: Somewhat fair (4) to Poor (5)

Besides the subjective assessment conducted by the pilots, simulator data was evaluated to examine whether task performance parameters and flight path trajectories were inside the tolerances and whether pilot comments and assessment match the data. Table 3 shows the specified performance tolerances for the CAT-A RTO scenario. The ROC and GS refer to the take-off segment of the manoeuvre, whereas the touchdown point rate of descend (ROD) and GS refer to the descent phase.

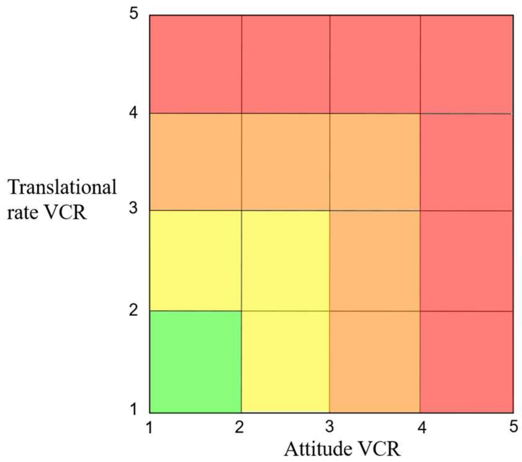


Figure 7. Graphic for illustration of VCR results

The tolerances are derived from the AW109 rotorcraft flight manual (RFM) instructions and have been specified through discussion with researchers, flight test engineers, and pilots. The touchdown tolerances were only relevant for the NLR simulator test campaign as the DLR campaign did not put emphasis on evaluating the helicopter touchdown phase due to the lack of a ground contact model in the AVES simulation model.

Table 3. CAT-A RTO performance tolerances

	Desired	Adequate
Take-Off ROC	350±50 ft/min	350±100 ft/min
Take-Off GS	4-5 knots	3-6 knots
Touchdown ROD	<400 ft/min	<500 ft/min
Touchdown GS	<5 knots	<10 knots
Touchdown Point	On X (32x32 ft)	On concrete (43x43 ft)

DLR TEST RESULTS

Pilot-in-the-loop simulator test campaigns at DLR were conducted with three pilots, having experience in flight testing and certification. The total amount of hours spent flying several helicopter types is listed in Table 4 for all three pilots. In order to exclude possible lack of training from the equation, all pilots got enough attempts to perform the task until the pilot agreed to show his/her best possible performance for the respective FoV-setting.

Table 4. Pilot experience of DLR campaign

Pilot	Flight Hours	Most frequently flown helicopter type
A	6850	Bo105
B	1300	Bo105
C	3700	AW139

Visual cue rating

All pilots have performed the CAT-A RTO with the four FoV-settings. For every setting, VCRs were awarded after each test run inside the cockpit by using a tablet. This allowed the pilots to directly assess and comment on their perception during the scenario and prevented information from being lost. The combined average VCRs for translational rate and attitude are illustrated in Figure 8.

It can be seen that the VCRs of 'AVES' and 'RoCS Sim' resulted in the same combined rating inside the green area. This area can be interpreted as 'good' to 'somewhat good', according to the linear VCR scale in Figure 6. This similarity was expected and matches the pilot comments. During RTO, pilots tried to maintain sight of the helipad at all time. Both FoV-settings have the same available vertical down-view. Therefore, all pilots managed to see the whole helipad throughout the manoeuvre. The 220° horizontal FoV was not perceived as objectionable compared to the default AVES 240°. For a CTO manoeuvre, the VCRs would have most likely been worse (numerically higher) for the 'RoCS Sim' than for the AVES setting due to a FoV-limitation (+20° instead of +35°) in the up-view. After exceeding TDP height, enough FoV needs to be provided for the pilot in order to estimate the flight path ahead. However, this area of the FoV is not relevant for the RTO manoeuvre.

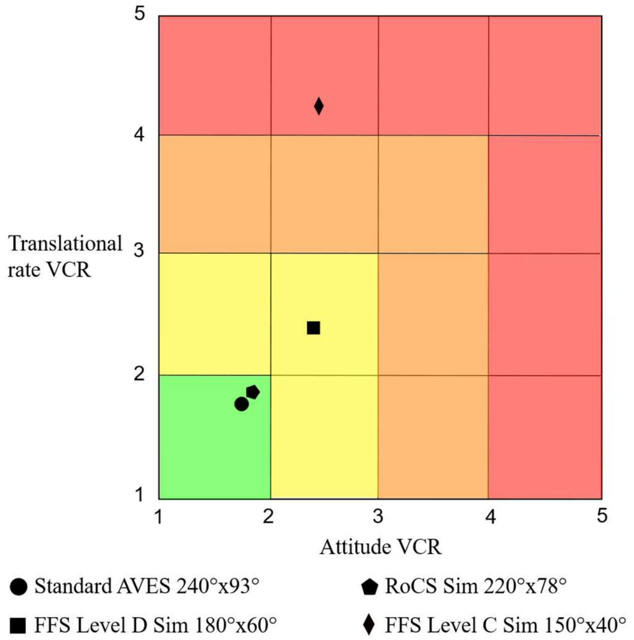


Figure 8. Combined average VCRs for translational rate and attitude for different FoV settings.

Performing the RTO with a 'Level D' FoV limitation resulted in a worse combined VCR rating compared to the two settings discussed before. Pilots were not able to maintain sight of the helipad during the complete manoeuvre due to the vertical FoV limitation. The horizontal limitation did not disturb the pilot too much since the manoeuvre did not require observation of the outside world through cockpit side windows. This limitation was only noticeable in the peripheral view.

For the 'Level C' setting, both the horizontal and vertical FoV was assessed as disturbing and insufficient. This led to a combined VCR close to poor. Due to a total vertical FoV of 40°, the helipad was no longer visible through the chin windows. Pilot task strategy had to be adjusted in order to increase situational awareness and complete the task. Visible objects in the vicinity of the helipad were used as a reference. However, the only option to reasonably judge the flight path with such a limitation is by looking at the instruments. Additionally, the horizontal FoV limitation made the pilots feel uncomfortable and insecure when flying backwards.

Objective results

Figure 9 illustrates a sketch of the confined take-off and landing area in AVES. Due to buildings and trees in the vicinity of the helipad, the pilot's only option is to take off in a south-easterly direction by performing a back-up manoeuvre (in a north-westerly direction). Whether the pilot stayed inside the prescribed tolerances during the manoeuvre can be verified by analysing objective simulator data. This enables a comparison of the task performance between the different FoV-settings.

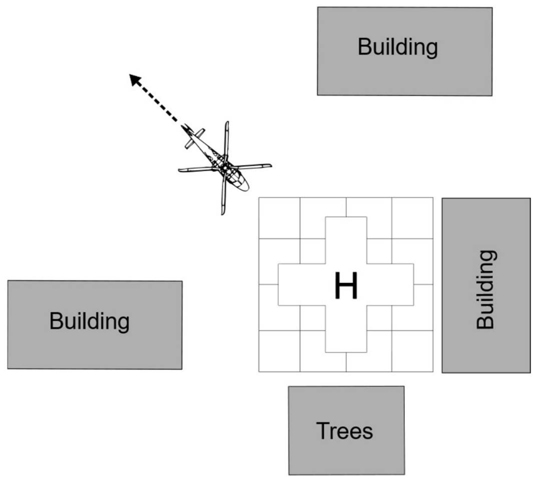


Figure 9. Sketch of confined area for CAT-A RTO scenario built in AVES

Figure 10 shows a topview (xy-plane) of the flight path performed by one of the pilots. Lateral position is plotted against longitudinal position with respect to the take-off position. Pilots were requested to stay on the flightpath during the manoeuvre and avoid deviations in lateral direction. As in the AW109 RFM, no specific performance tolerances have been defined for lateral flight path deviations. By comparing the simulator data of all three pilots, a similar trend is apparent. For the 'Level C' setting, pilots had difficulties in staying on the flight path due to the loss of sight to the helipad. One pilot started drifting to the right during the manoeuvre (see green line in Figure 10) and commented that he was searching for reference points in the environment.

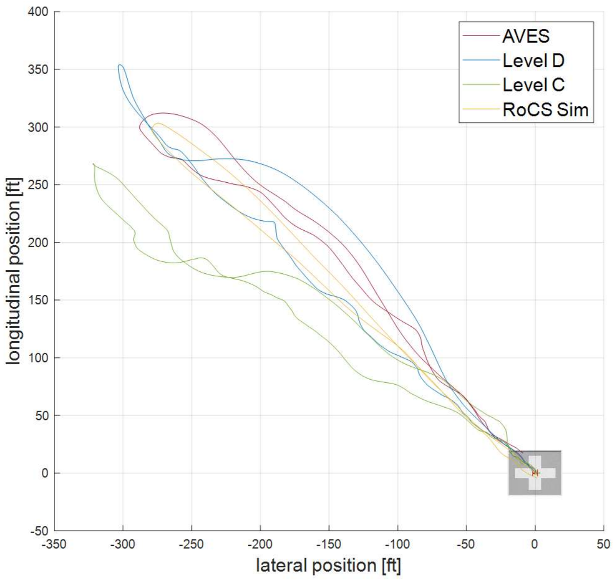


Figure 10. Performed RTO flight path in xy-plane (one pilot)

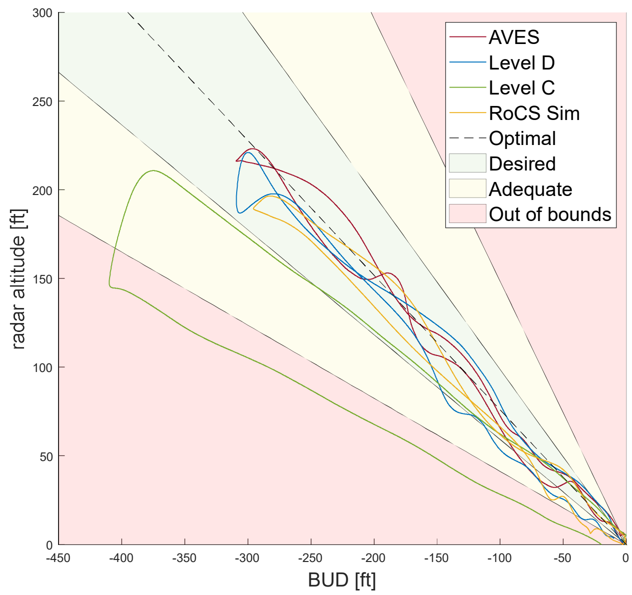


Figure 11. Performed RTO flight path in xz-plane (one pilot)

As opposed to the flight path in the xy-plane, ROC and GS tolerances were defined for the xz-plane. Whether the pilot stayed inside 'adequate' or 'desired' performance is illustrated in Figure 11, where radar altitude is plotted against the back-up distance (BUD). All pilots were told to reject the take-off at a radar altitude of 200 ft. Staying inside the 'desired' green area indicates that an average ROC between 300 and 400 ft/min as well as an average GS of 4-5 kts has been maintained. Entering the yellow 'adequate' area implies that the boundaries for 'desired' have been exceeded by ±50 ft/min ROC and ±1 kts GS.

The pilot task performance data depicted in Figure 11 shows only minor differences between the three FoV-settings 'AVES', 'Level D' and 'RoCS Sim'. The pilot managed to stay inside 'desired' for the majority of the scenario. In the area of low altitudes, the flight path trajectory plots traverse the 'adequate' area during take-off and decent. However, it needs to be considered that the boundaries in that area are closer to each other due to the funnel shape. During the task conducted with a 'Level C' FoV-setting, the pilot stayed between 'desired' and 'adequate' during the take-off. However, after rejecting the take-off, a major fall in altitude was experienced which was not corrected by the pilot, and therefore, resulted in a shallow flight path trajectory in the 'out of bounds' area. Although this large drop in altitude is not present in data from the other two pilots, GS and ROC 'adequate' targets have generally not been met by either pilot performing the scenario with a 'Level C' setting.

After analyzing the general comments as well as objective and subjective assessment data from all three pilots, it can be derived that a minimum horizontal FOV of 190° is recommended for performing a CAT-A RTO manoeuvre so that peripheral vision is not obstructed and distracting. Conducting this task with a 'Level C' FoV is insufficient in terms of both the vertical and the horizontal FoV. Only minor differences were noticeable between the default AVES and the 'Level D' setting. These differences can be explained by the vertical FoV limitation in that the 'Level D' setting did not provide enough vertical down-view FoV for the pilot to maintain full sight of the helipad through the chin window during the manoeuvre. As opposed to the down view, the vertical up-view is not considered as crucial. This was confirmed by the assessment of the 'RoCS Sim' configuration where the up-view angle was limited to +20°.

NLR TEST RESULTS

The simulator test campaign at NLR investigated whether the standard projection system in a simulator can be substituted by a VR device for performing a CAT-A RTO manoeuvre. For this purpose, three pilots tested the projection system, the Varjo, and the Pimax. Pilots involved in NLR's test campaign and their experience are listed in Table 5.

Table 5. Pilot experience of NLR campaign

Pilot	Flight Hours	Most frequently flown helicopter type
C	350	CH-47
D	3500	NH90
E	3700	AW139

Objective results

The simulator data gathered during the three experiments is to a large extent unsuitable for drawing direct comparisons between the different pilots. This is due to the fact that the parameter settings have been varied and refined throughout the experiments and the tolerances and flight procedures have not been kept constant due to limitations encountered during the test activities (e.g. lack of a chin window). Consequently, this resulted in adaptations to the test matrix, which was expected since iterations of the methodology are considered part of the RoCS research. As a result, in this paper exclusively the objective performance data of Pilot E is presented and discussed. However, the subjective data and general experiences of Pilot C and D are considered relevant since these results are not bound to simulator settings and test variables, but to the specific visual system in relation to the manoeuvre. Pilots were allowed to familiarize and practice the manoeuvre for each condition. Also, runs have been performed multiple times until the best possible performance, for that specific visual system, was reached according to the pilot.

Similar to the DLR campaign, flight path trajectories from a side view (xz-plane) and a top down perspective (xy-plane) have been analysed. The TDP height varied between 70 ft and 400 ft. At first glance, the trajectories do not reveal considerable systematic differences between the visual systems (Figure 12), though the pilot commented that piloting strategy and scanning patterns were notably different. In the BUD versus height plots in can be seen that the pilot was capable of maintaining the desired flight path for the majority of manoeuvre. As in Figure 11, desired performance is visualized by the green funnel and the optimum flight path is represented with a dashed line. The yellow funnel represents the adequate performance tolerances, while the red areas indicate being 'out of bounds'. The results show that the desired performance has been obtained for nearly all stages of the take-off and rejection trajectory for all three engine failure heights (i.e. 70 ft, 250 ft, and 400 ft), and all three visual systems. However, only short parts of the RTOs performed with VR with the engine fail height at 250 ft are according to adequate standards. A brief period of being out of bounds (under tuck) is observed for the Varjo condition with engine failure height at 250 ft and 400 ft. Due to the funnel shape of the flight path angles (origin is set at 3 ft over the helipad cross), this is a somewhat exaggerated result as the tolerances reach only a few feet in magnitude.

Regarding the top view visualisations, the flight paths appear to be rather diffuse. No clear trend in lateral and longitudinal position over time per visual system is observed. Moreover, no tolerances for these variables have been prescribed other than maintaining a straight backward movement with a 4-5 knots GS during the take-off and landing on the helipad after rejection. This task has been performed satisfactorily for all conditions by Pilot E. Likewise, the point of initial touchdown was within desired or adequate tolerances for all runs.

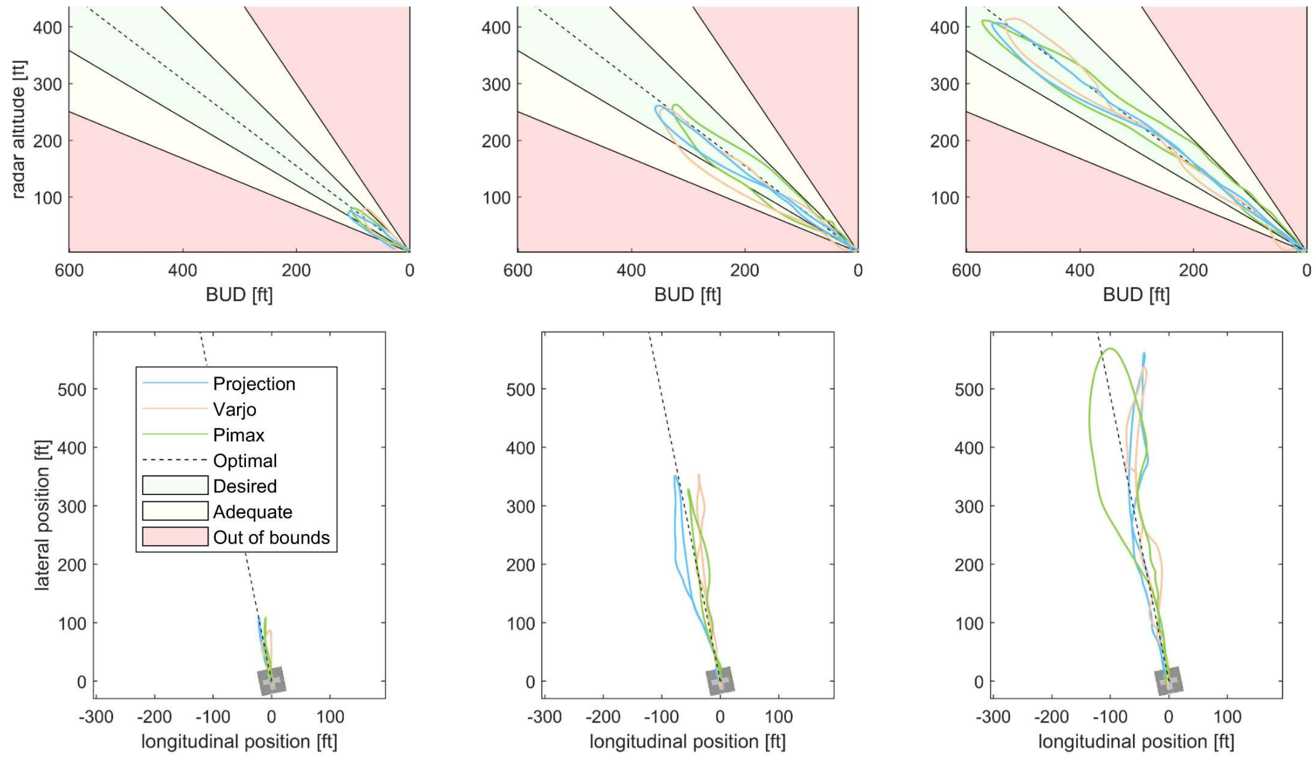


Figure 12. Pilot E flight path trajectories for the CAT-A RTO for engine failure height at:

(a) 70 ft **(b) 250 ft** **(c) 400 ft**

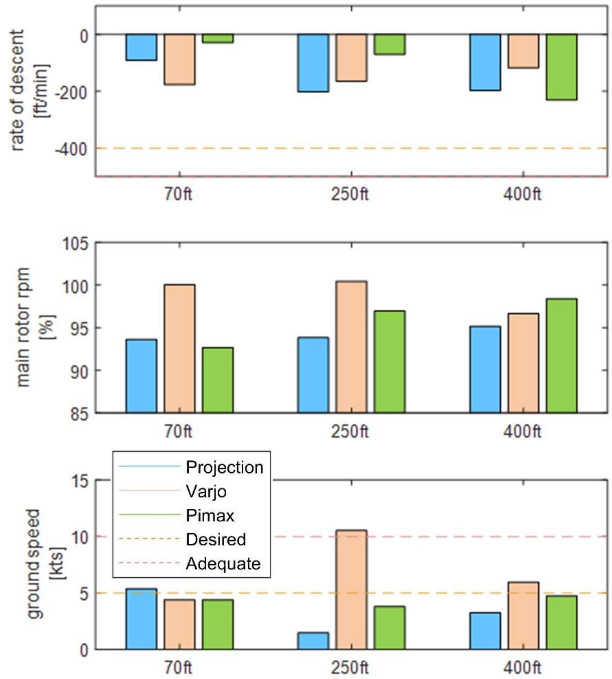


Figure 13. RTO Touchdown performance measurements per engine failure height

Looking to the other performance standards (listed in Table 3), referring to the instant of touchdown, differences between the visual systems can be observed. The instant of touchdown is determined as the last discrete 'observation' prior to touchdown. These data are presented in Figure 13. The ROD, which is a measure for the force experienced by the undercarriage during touchdown, remained well within limits, especially for the Pimax condition, where ROD values below 100 ft/min were observed. Despite the fact that for the touchdown main rotor RPM no tolerances are specified, these data hold relevant information as proper 'cushioning' can be detected. The main rotor RPM at touchdown indicates whether the pilot was able to convert the helicopters kinetic energy, comprising forward movement and rotating blades, into a decrease of ROD.

The most distinct difference between the visual systems observed for the performance of Pilot E is the shallow approach during the Varjo condition (as can be seen in Figure 12) being accompanied by a relatively high GS and main rotor speed. For the 250 ft engine failure height condition a GS beyond tolerances was observed for the moment of touchdown. Also, for the 400 ft engine failure height a suboptimal GS was observed. This suggests limited possibilities to obtain forward movement and height above ground cues as generated by the Varjo VR device. This could be due to the limited FoV (despite the unlimited FoR). Using the projection visual system, Pilot E consistently landed with a nearly vertical descent gradient (i.e. with low ground speed). Combined with the low rotor RPM and moderate touchdown rate of descent, the data suggests a relatively aggressive or somewhat early landing flare.

Visual cue rating

The visual cue ratings of the three pilots have been averaged. The most limiting translational and attitude values are plotted in Figure 14.

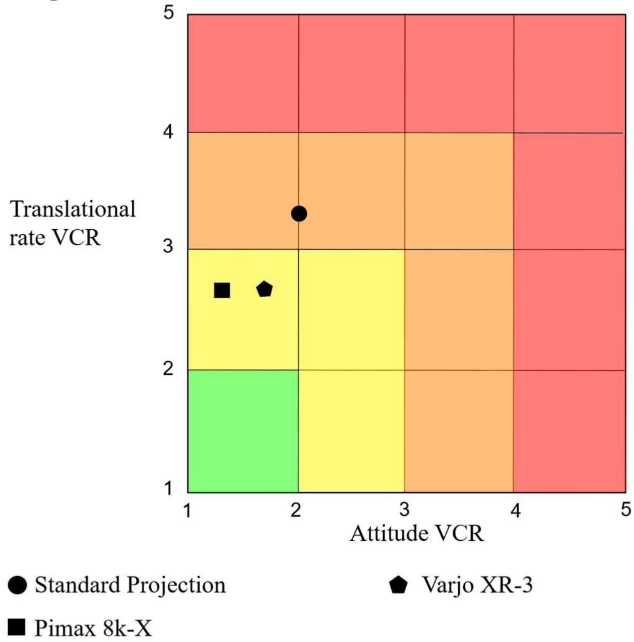


Figure 14. Average VCRs for translational rate and attitude rate for different visual systems

The standard projection method received the lowest (numerically highest) score, both for the translational rate and attitude VCR. This is in line with the pilots' comments, which referred to the lack of a chin window and, therewith, the inability to maintain sight of the helipad. The Varjo and Pimax show improved VCR compared to the projection system, particularly due to the availability of a chin window in VR. Based on the pilots' comments, the difference between the VCR of the Varjo and Pimax is caused by the availability of a larger FoV for the Pimax, which was preferred over the high-resolution focus area of the Varjo. Especially for the CAT-A RTO manoeuvre, the performance during rejection is improved by enabling the pilot to overview as many visual reference points as possible. This includes, aside from the helipad, having peripheral view of buildings and trees.

The inability of the Pimax to display a highly detailed cockpit view in VR (in contrast to the Varjo) affects the execution of the manoeuvre to a lesser extent. Although the boundaries of the FoV in the Pimax appear blurry and to some extent distorted, this was still experienced as being of added value. It should be noted that when the RTO is performed in an environment without additional objects to the helipad (e.g. an offshore oil rig), these visual references would not exist and only the chin window would provide adequate visual cues. Additionally, the colour contrast of the helipad and associated markings was experienced by the pilot as inadequate, which reduced the perception of height above ground. This complicated the timing of the landing flare to cushion the landing, which is critical in the terminal phase of the landing. Besides a higher contrast, the usage of a pattern overlay would most likely have assisted during the final seconds before touchdown.

DISCUSSION

In the test campaign conducted at DLR, the importance of available FoV for performing a CAT-A RTO manoeuvre was investigated by testing different FoV-settings. Pilots had difficulties in performing the manoeuvre when the FoV is limited to an extent that the vertical limitation prevents the pilot from maintaining sight of the helipad. Also, limiting the horizontal FoV to less than 180° has the consequence of an obstructed peripheral vision for the pilot. In order to be able to judge forward and aft movement of the helicopter, the pilot has to turn his/her head once in a while, although the flight test engineer provided the pilot with information about GS and ROC throughout the flight task.

In the NLR test campaign the usage of VR devices was compared to a standard cylindrical projection system. Despite the differences in technical specification (large versus small FoV and low versus high resolution) minor apparent differences in objective performance data were observed for the VR devices. The flight path trajectories and specified tolerances are mostly satisfactory for all conditions. Only for the Varjo VR device, forward movement cueing appeared to be slightly more challenging because of limited peripheral visual references. The availability of a large FoV (Pimax) is preferred over a high resolution (Varjo) for the selected task. Although difficulties were experienced to focus on the cockpit instruments during the rejected take-off, this appeared to be less of a concern after a stable glide to the helipad was achieved and sight was kept through the chin window. Therefore, no shifting of focus was required.

In addition to the pilots' comments mentioned in the results section, several general remarks are worth highlighting. Although all pilots appeared to familiarize themselves relatively quickly with the simulator (flight model, cockpit layout, etc.), the manoeuvre, and the visual systems, it was clear that for those pilots with experience on the AW109, the deviations from AW109 specific characteristics and procedures were considered objectionable and are to be addressed in subsequent test campaigns within the RoCS project. The discrepancies with the real aircraft were in large part due to data unavailability. For example, no sound cues were provided in the simulator as no data was available to generate them. Lacking such a cue, the engine failure was announced by the experiment lead. However, the lack of a low rotor speed warning or rotor/engine noise to provide aural cueing of rotor speed was considered objectionable because this meant that only head-down information on rotor speed was available to the pilot in a phase where all his/her attention is required to properly time the landing flare using outside visual cues.

Also, no exact replica of the AW109 cockpit instrument panel was available for the testing at NLR and DLR. Instead, generic engine torque and rotor speed instruments were used. However, pilot comments suggest that the location of the instruments was not adequately similar to the AW109, affecting the scanning pattern of the pilot even further.

Furthermore, it was observed that the test pilots were prone to developing a strategy to complete the manoeuvre satisfactory, compensating for the lack of cueing for each test configuration. The learning curve was apparent in the execution of the task, which was a driving factor in the decision to allow the pilots time to get acquainted with each test set-up. A greater population of pilots and experiments in combination with counter-balancing the scenarios would serve to reduce this effect.

Finally, in an ideal situation the VCR questionnaires would be administered among pilots who experienced the exact same test condition. This was not the case for the NLR campaign since the determination and refinement of the test matrix is a large part of the RoCS project and therefore, it was decided to improve the experiment design when this was possible instead of sticking to the predefined test conditions. Furthermore, it was judged that changes in the parameter settings would have a comparatively small impact on the overall subjective experience of the visual systems.

CONCLUSIONS AND FUTURE RESEARCH

From the CAT-A RTO visual cue investigation presented in this paper, the following can be concluded:

- For a standard projection system, a minimum of 190° horizontal FoV is recommended so that peripheral vision is not obstructed.
- The angle of vertical down-view should be adequate for the pilot to maintain sight of the helipad during the manoeuvre. A minimum angle of -45° is suggested.
- A chin window is evidently required for the task, whether it is provided by the cockpit layout or simulated in the virtual environment.
- Limitation in vertical upper-view FoV (e.g. +20° instead of +35°) is feasible since this area of the FoV was not considered as crucial for satisfactory task performance.
- The Pimax was determined to be the most suitable amongst the tested VR devices for the tested manoeuvre, mainly due to the larger available FoV. Nonetheless, higher resolution could lead to major improvements, especially for near-ground scenarios.
- Positive results are found regarding the use of VR for rotorcraft certification purposes, which encourages to extend research in this field.

This investigation served as an initial step towards the development of guidelines for simulators that can be used for compliance demonstration during the certification process of future rotorcraft. Besides the visual cueing system, an individual cueing fidelity assessment of other simulator components (e.g. motion cueing system) needs to be conducted in future simulator test campaigns before ensuring that the overall simulator cueing fidelity is fit for purpose. If a certain overall fidelity might not be sufficient for fully simulating a given certification task and, therefore, for replacing flight test, it might still be awarded partial credit for compliance demonstration, which would result in the reduction of total flight test hours needed.

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