Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

NLR-TP-2013-559

Helicopter Flight in a Degraded Visual Environment

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Executive summary

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Safety records showed that the highest frequency of occurrence of accidents with helicopters involved in Degraded Visual Environment (DVE) mishaps was with the small types, and for a few special conditions or scenarios, viz. the Inadvertent entry into IMC (Instrument Meteorological Conditions), called ‘IIMC’, and the Controlled Flight Into Terrain scenario, called ‘CFIT’. Therefore, the National Aerospace Laboratory NLR, under contract to the European Aviation Safety Agency ‘EASA’, performed a project called ‘Helicopter Flight in a Degraded Visual Environment’. The objective of this project was to provide a study on unintended helicopter flight into a degraded visual environment during VFR (Visual Flight Rules) operations.

Description of work

The first step in the project is the performance of a literature survey with one of its objectives to identify candidate technical concepts which are basic, simple systems fit to be mounted in a small helicopter. The most promising technical concepts are implemented in NLR’s (fixed-base) helicopter simulator, called the Helicopter Pilot Station (HPS). These were:

- A visual cue enhancing device, making the pilot aware of his attitude in roll and pitch (not quantitatively), called a Malcolm Horizon.
- A concept that has been adopted from the fixed-wing fighter aircraft domain for recovery from unusual attitudes, usually projected onto a HUD (Head-Up Display), called the “HUD Orange Peel”.

This report is based on a presentation held at the European Rotorcraft Forum, Moscow, 3-6 September 2013.

- A concept providing peripheral cues consisting of LED lights, mounted on strips placed in the pilot's peripheral vision and which is lit from the bottom (cabin floor) up to the point where it is on the horizon, seen from the pilot's eye reference point.
- The use of audio signals in the form of a Helicopter Terrain Avoidance and Warning System (HTAWS).

NLR's (fixed-base) helicopter simulator was modified to provide the pilot with a field-of-view, which better matches that of a small helicopter, in this case an R44. Piloted simulation tests were performed in order to find out to what extent these concepts did really help improve the visual cues, flight safety, and to determine the pilot's acceptance of these devices in the cockpit of a small helicopter.

Results and conclusions

From the experiments it is concluded that the HUD Orange Peel provided the best visual enhancement cues. The Malcolm Horizon was the second best visual enhancement concept in terms of Usable Cue Environment as it was simple to interpret. The HTAWS audio concept was greatly appreciated, while the working of peripheral cues in the LED concept did not materialize in the way it had been expected.

Applicability

Implementation of the concepts depends upon the maturity level and the TRL level they are at. Presently they are not mature enough to be installed already in small rotorcraft. For example, the design of both the Malcolm Horizon and the HUD Orange Peel is not yet complete since additional features need to be added to the displays.

All concepts could act as a confidence builder. When any of these, or other, concepts are implemented it is highly recommended to combine its introduction with an awareness campaign to highlight that the concerning concept is meant as an escape / prevention concept and specifically not to extend the operational limits.

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Summary

The National Aerospace Laboratory NLR, under contract to the European Aviation Safety Agency ‘EASA’, performed a project called ‘Helicopter Flight in a Degraded Visual Environment’. The objective of this project was to provide a study on unintended helicopter flight into a degraded visual environment during VFR (Visual Flight Rules) operations. It included investigating the feasibility and effectiveness of a number of aids for pilots to enhance the visual cueing and situational awareness (e.g. attitude, terrain proximity) to mitigate the safety hazards associated with DVE.

Safety records showed that the highest frequency of occurrence of accidents with helicopters involved in DVE mishaps was with the small types, and for a few special conditions or scenarios, viz. the Inadvertent entry into IMC (Instrument Meteorological Conditions), called ‘IIMC’, and the Controlled Flight Into Terrain scenario, called ‘CFIT’. For these scenario’s various concepts have been identified which are basic, simple systems fit to be mounted in a small helicopter. The ones considered to be the most promising are:

- A visual cue enhancing device, making the pilot aware of his attitude in roll and pitch (not quantitatively), called a Malcolm Horizon.
- A concept that has been adopted from the fixed-wing fighter aircraft domain for recovery from unusual attitudes, usually projected onto a HUD (Head-Up Display), called the “HUD Orange Peel”.
- A concept providing peripheral cues consisting of LED lights, mounted on strips placed in the pilot’s peripheral vision and which is lit from the bottom (cabin floor) up to the point where it is on the horizon, seen from the pilot’s eye reference point.
- The use of audio signals in the form of a Helicopter Terrain Avoidance and Warning System (HTAWS).

All above concepts are implemented in NLR’s (fixed-base) helicopter simulator, called the Helicopter Pilot Station (HPS) which is for this purpose modified to provide the pilot with a field-of-view, which better matches that of a small helicopter, in this case an R44 alike helicopter. Piloted simulation tests were performed on the HPS in order to find out to what extent these concepts did really help improve the visual cues, flight safety, and to determine the pilot‘s acceptance of these devices in the cockpit of a small helicopter. During the simulation trials both objective and subjective data were recorded including eye movements. Six non-Instrument Rated General Aviation helicopter pilots and one EASA test pilot and engineer participated.

From these experiments it is concluded that the HUD Orange Peel provided the best visual enhancement cues, but attracted focal attention of the pilot at the expense of looking more around outside. The Malcolm Horizon was the second best visual enhancement concept in terms of Usable Cue Environment. It was simple to interpret and pilots were quick to understand what the line meant and the handling qualities ratings improved. The HTAWS audio concept was greatly appreciated. The pilot comments were very favourable, the Time-To-Impact that was used as a threshold was much appreciated by the pilots as a simple concept. The eye tracking data showed that with the HTAWS more time was spent looking at the instruments than with ‘no concept’. The working of peripheral cues in the LED concept did not materialize in the way it had been expected. There are ways to define better peripheral cueing mechanisms to improve the situation, e.g. by making the roll and pitch attitude cue not a steady-state cue but a moving one.

All concepts could act as a confidence builder. When any of these, or other, concepts are implemented it is highly recommended to combine its introduction with an awareness campaign to highlight that the concerning concept is meant as an escape / prevention concept and specifically not to extend the operational limits.

Contents

Abbreviations

AGL	Above Ground Level
AHRS	Attitude and Heading Reference System
CAA	Civil Aviation Authority
CFIT	Controlled Flight Into Terrain
CHR	Cooper-Harper Rating
DVE	Degraded Visual Environment
EASA	European Aviation Safety Agency
EHSAT	European Helicopter Safety Analysis Team
EU	European Union
GPS	Global Positioning System
HPS	Helicopter Pilot Station
HTAWS	Helicopter Terrain Avoidance and Warning System
HUD	Heads-up Display
ICQ	In-Cockpit-Questionnaire
IFR	Instrument Flight Rules
IIMC	Inadvertent entry into IMC
IMC	Instrument Meteorological Conditions
KIAS	Knots Indicated Airspeed
LED	Light-emitting Diode
MTOW	Maximum Take-Off Weight
NLR	National Aerospace Laboratory
PEQ	Post-Exercise Questionnaire
PIO	Pilot-Induced Oscillation
RF	Risk Factor
TRL	Technology Readiness Level
TTI	Time To Impact
VFR	Visual Flight Rules

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1 Introduction

1.1 Background

Helicopter flights are particularly vulnerable when exposed to conditions associated with a “Degraded Visual Environment” (DVE). A big issue with a degraded visual environment is the safety hazard involved. From safety records it turned out that the highest frequency of occurrence of accidents with helicopters involved in DVE mishaps was with the small types (Robinson R44 like), and for a few special conditions or scenarios, viz. the Inadvertent entry into IMC (Instrument Meteorological Conditions), called ‘IIMC’, and the Controlled Flight Into Terrain scenario, called ‘CFIT’.

Therefore, the National Aerospace Laboratory NLR, under contract to the European Aviation Safety Agency ‘EASA’, performed a project called ‘Helicopter Flight in a Degraded Visual Environment’, in order to provide a study on unintended helicopter flight into a degraded visual environment during VFR (Visual Flight Rules) operations, investigating the feasibility and effectiveness of a number of aids for pilots to enhance the visual cueing and situational awareness (e.g. attitude, terrain proximity) to mitigate the safety hazards associated with DVE. This paper is based on the final study report of the project on Helicopter Flight in a Degraded Visual Environment, Ref [1].

Preliminary work in the area of visual cueing was performed by the CAA (Ref. [2]), who evaluated basic aspects of visual cueing and the guidance process the pilots adopts in order to perform his flying task.

1.2 Methodology

The first step in the project is the performance of a literature survey to:

- identify existing safety & operational data;
- identify candidate technical concepts which are basic, simple systems fit to be mounted in a small helicopter;
- characterize supporting technical enablers and;
- gather existing helicopter transport data.

Subsequently, the most promising technical concepts are implemented in NLR’s (fixed-base) helicopter simulator, called the Helicopter Pilot Station (HPS).

Simultaneously, the simulator is modified to provide the pilot with a field-of-view, which better matches that of a small helicopter, in this case an R44. For this, the top instrument panel was taken out and replaced by a 19" monitor, on which the R44 Raven instrument panel instrument layout was projected. An estimate of the outside optical field-of-view of the HPS, when equipped with the reduced instrument panel, is given in Figure 1.

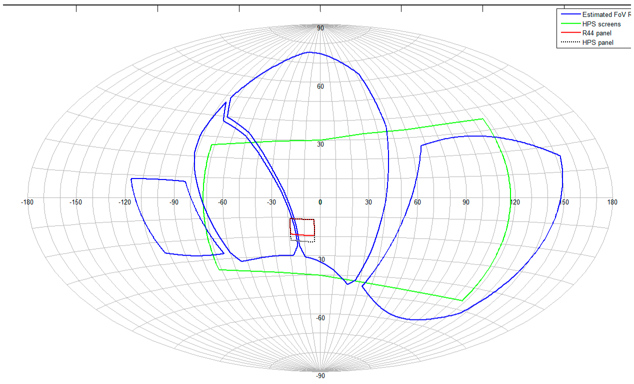


Figure 1 Optical field-of-view from the pilot's eye reference point in the HPS, with the new 19" instrument panel, relative to the R44 helicopter

Piloted simulation tests were performed on NLR's (fixed-base) helicopter simulator in order to find out to what extent these concepts did really help improve the visual cues, flight safety, and to determine the pilot's acceptance of these devices in the cockpit of a small helicopter.

As experimental design, a so-called repeated measures or within-subjects design was used, where each pilot was offered all the visual and audio enhancement concepts on all the scenarios. In order to avoid learning effects the sequence of runs per scenario were randomized across pilots.

Six General Aviation helicopter pilots from the Dutch General Aviation Rotorcraft Pilots Association were randomly selected from all respondents to participate as subjects in the simulations. They were split equally into 2 groups, one with less than 300 flight hours (min. 90h, max. 280h), and one with more than 300 hours (min. 450h, max.1100h). The pilots were not instrument-rated. EASA participated for one day with one highly experienced experimental test pilot (10,000 h) and flight test engineer. They were subjected to most of the test conditions the other pilots had also been subjected to.

During the simulation trials both objective and subjective data is recorded. Objective data are flight-parameters that were registered within the flight simulator environment, such as airspeed, altitude, pitch and roll angle, etc., as well as eye tracker data. Subjective data, consisted of the entries made in the two questionnaires that were used, viz. the In-Cockpit-Questionnaire (ICQ) after each run, and the Post-Exercise Questionnaire (PEQ) after the exercise was completed.

Questions were asked about the workload experienced, the usefulness and acceptance of the enhancement concept, the safety level, the rotorcraft's handling qualities, the situational awareness experienced, the occurrence of a crash (and why), etc.

To further substantiate the recorded data use is also made of a lightweight head and eye movement tracking using a head-worn device which is recommended in situations where it is important for participants to have freedom of movement and/or where gaze must be measured over an unrestricted field of view. The eye tracker uses an infra-red camera, an infra-red light source and a semi-reflective visor to measure the reflection of the retina. This provides information about the position of the eye. Mounted on the eye tracker device is the receiver of the magnetic head-tracker. This device measures the position and orientation of the head in space using the magnetic field generated by the transmitter.

2 Literature Review

In order to identify existing safety & operational data, identify candidate technical concepts, characterize supporting technical enablers and gather existing helicopter transport data a literature review is performed.

2.1 Safety & operational data

An essential part of the study is the identification of safety and operational data to derive key hazardous situations for VFR pilots in DVE conditions. For this purpose primarily the accident database of the European Helicopter Safety Analysis Team (EHSAT)[1] has been consulted.

In order to identify the key hazardous situations a selection of the relevant accidents was made by using a selection of the taxonomy codes that could be linked or related to DVE related accidents. The selected codes incidences 707 times, linked to 278 different accidents. From these 278 accidents, 96 could be linked to DVE either though DVE reported conditions or, when these were not reported, to the type of accident, i.e. Controlled Flight Into Terrain (CFIT) etc. These accidents span the period of 2000 – 2008. Note that for the years 2000 to 2005 the dataset is complete; accidents at a later date have not all been included in the database yet. Of these 96 accidents, 50 were rated as a 'probable' (more likely p>0.5) DVE-related event and 46 as 'possible' (less likely, p<0.5) DVE-related event. For those rated 'possible' the type of accident (e.g. CFIT) can be DVE-related but no weather/visibility information could be retrieved to

1 EHSAT is the analysis team of the European Helicopter Safety Team (EHEST) which is the European counterpart of the International Helicopter Safety Team (IHST) and falls under the European Strategic Safety Initiative (ESSI). The main objective of these teams is to achieve 80 percent fewer helicopter accidents by the year 2016, as compared to 2006 levels, see also http://easa.europa.eu/essi/ehest/.

confirm this. The identification of key hazardous situations is based on the 50 'probable' (more likely) DVE accidents.

Based on the description and information from the 50 'probable' (more likely) DVE-related accidents a further classification of accident types has been derived. From this further classification it is concluded that the case 'CFIT: loss of ground texture[2] and the 'Inadvertent entry into IMC[3] have the highest rate of occurrence.

2.2 Candidate technical concepts

A number of technical concepts have been reviewed. Generally they fall into 4 categories, viz.

1. enhanced attitude cueing devices,
2. emergency, recovery indication on a HUD,
3. cueing devices using peripheral vision,
4. sound cueing for approaching terrain, obstacles, etc.

Specific technical concepts for each of the above categories are further described in chapter 4.

2.3 Technical enablers

Each candidate technical concept cannot be installed or implemented without additional enablers, systems or devices needed to provide the data the enhancement concepts require in order to function properly.

An attempt was made to compare and rank order the various visual cue enhancement concepts in terms of the following criteria:

1. performance,
2. maturity level (Technology Readiness Level 'TRL'),
3. weight/mass,
4. cost to purchase or develop,
5. level of additional training required.

Based in this ranking 4 concepts were identified, one in each category (see paragraph 3.2). These are further described in chapter 4.

2 Either no ground textures due to being in cloud/fog or due to snow-covered terrain resulting in loss of horizon or ground texture cues.

3 The pilot became disoriented in, or close to, a cloud and lost control.

2.4 Helicopter transport data

The final part of the literature review is the identification of relevant classes of rotorcraft to be considered for assessing the proposed concepts that could assist in mitigating the key hazardous situations for VFR pilots encountering DVE conditions.

For this, use has been made of an online database containing all worldwide registered civil rotorcraft (Ref. [3]). Using the dataset of December 2010, a selection was made of the relevant countries. For this purpose the 27 EU member states plus 4 were selected in line with EASA's annual safety review.

A total of 7641 rotorcraft registrations were identified, representing 94 different types. These are grouped in three different classes of rotorcraft based on their Maximum Take-Off Weight (MTOW). Class 1 rotorcraft are predominantly light single-engined rotorcraft (either piston 'P' or turbine 'T' powered) mainly operated under Visual Flight Rules (VFR). Class 2 rotorcraft contains typically single or twin-engined turbine powered rotorcraft, operated both under VFR and Instrument Flight Rules (IFR) and class 3 rotorcraft contains the multi-engine rotorcraft, predominantly operated under IFR. Table 1 gives an overview of the different classes.

Table 1 Rotorcraft classification

Class	1	2	3
MTOW (kg)	≤ 2250	2250 - 3175	> 3175
Engines	1P / 1T	1T / 2T	2T / 3T
Flight rules	VFR	VFR / IFR	IFR
# of types	44	13	37
# registrations	4910	1438	1293
Typical type (# registrations) (flight hour estimation)	R44 (1106) (608300)	EC135 (441) (88200)	AS 332 (91) (89180)

3 TECHNICAL CONCEPTS

This chapter describes the 4 candidate technical concepts as identified in the literature review (chapter 2) and as tested during the simulation trials.

3.1 Malcolm Horizon

This visual cue enhancing device makes the pilot aware of his attitude in roll and pitch (but not quantitatively). A typical example of the Malcolm Horizon is given in Figure 2.

Figure 2 Extended horizon line or Malcolm Horizon (MH) concept

Through the whole cockpit a horizon line, the "Malcolm Horizon", is projected using any suitable device such as a scanning laser, reflecting off the wind screens and cockpit structure. In the implementation in the simulator a line was drawn in the visual system of the simulator that generated the visual cues. This Malcolm Horizon provides only pitch and roll information. Because of its "wide" angle the peripheral impression of attitude can be quite strong and compelling, which was the idea of this concept in the first place. Peripheral cues are "noted" and processed in the brain, but do not require attentive effort by the pilot to acquire.
As the above figure shows, in level flight in cruise the Malcolm Horizon passes just above, or through, the standby magnetic compass unit mounted on the central window style. This compass unit is often used as reference mark.

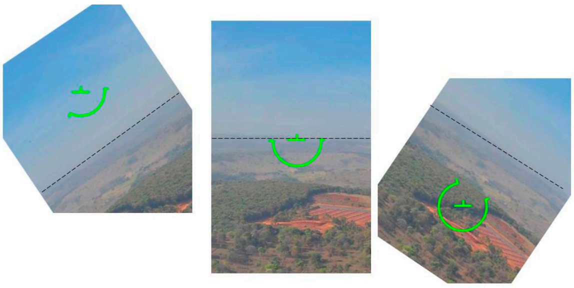
3.2 Orange Peel

This concept is one that has been adopted from the fixed-wing fighter aircraft domain for recovery from unusual attitudes, usually projected onto a HUD (Head-Up Display), hence called the "HUD Orange Peel". An example for a helicopter cockpit is given in Figure 3.

Figure 3 Head-Up Display (HUD) of attitude recovery using the "Orange Peel"

The green-coloured half circle with inverted ‘T’ is quite intuitive in helping the pilot to recover to level attitude from whatever attitude he might be in. A red short line underneath the symbol indicates height above ground. This red line or bar appears whenever the height has become less than some reference height, set at 500 ft. When the red line passes through the inverted ‘T’ the rotorcraft will have reached the ground.

Below 3 sequences are given to show what the HUD Orange Peel symbol presents in the various attitudes. The actions indicated are to be performed in order to resume straight and level flight.



a) push down and roll left b) no action c) roll right and pull up

Figure 4 Several sequences of the HUD Orange Peel

The “length” of the peel, i.e. how much it encompasses the inverted T, is proportional to the pitch angle, while the “rotation” of the peel depends upon the roll angle. Note that the symbology, presented on a (wide-angle) HUD, or else reflected off the windscreen, is fixed in position, i.e. it does not move across the HUD or window. It was argued that in case of such a recovery from a possibly extreme attitude the symbol the pilot then needs to look at should be in the same position, regardless of the flight path, in order not to add to the confusion that may already exist. This was also preferred by F-16 pilots (see Ref. [4]).

3.3 LED concept

It was hypothesized that for orientation or attitude awareness the pilot will pick up cues from his peripheral vision. This novel concept consists of, in this case, yellow-coloured LED lights, mounted on strips placed in the pilot’s peripheral vision, that are lighted from the bottom (cabin floor) up to the point where it is on the horizon, seen from the pilot’s eye reference point, see Figure 5. When in a banked attitude one strip of LEDs is then lighted further than the other strip, the idea being that the pilot will use this to determine a measure of roll angle. By using a third strip in front of the pilot it was thought that the differential LED information between the front and the 2 rear strips of LED lights would give pitch information in the same way.

Figure 5 LED lights mounted in the peripheral view of the pilot

Also a cue of the vertical speed was added using upward running (red-coloured) lights to indicate a descent condition. Four of those red-coloured cues are also shown in Figure 5. Whenever there is a sink rate they appear, and the speed at which they are traveling upwards depends on the actual rate of descent. In case of a climb they will disappear.

3.4 HTAWS

Another type of cueing the pilot is by the use of audio signals, e.g. for approaching terrain ("TERRAIN AHEAD"), for too large a sink rate for the condition that one is in ("SINK RATE, SINK RATE"), etc. This concept is referred to as the Helicopter Terrain Avoidance and Warning System (HTAWS).

Instead of the radio altitude the so-called Time-To-Impact 'TTI' was used, which is the ratio of the distance-along-the-line-of-sight to the ground impact point, divided by the inertial speed. If TTI comes between 20 and 30 seconds, the alert "TERRAIN AHEAD' will sound. When TTI becomes 20 seconds or less the warning "PULL UP" is given. As soon as the condition clears the respective voice alert ceases.

4 Scenario's

Three sceneries were selected from the available visual scene database in the fixed-base helicopter simulator, see Figure 6. The country of Albania was selected as this was NLR's available visual database that offered possibilities for undulated and mountainous terrain.

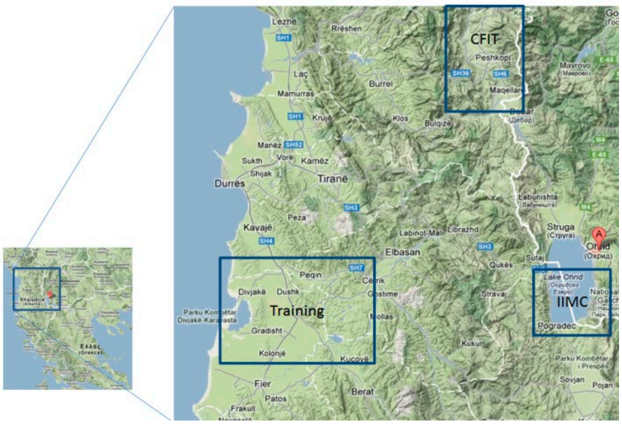


Figure 6 Areas selected for training, IIMC and CFIT scenarios

4.1 Training

To get acquainted with the simulator and aircraft model a training session was included in the simulation trails for which a scenery was defined. Pilots were trained in the area of Kavajě. This area has locally defined higher-detail areas.

4.2 Inadvertent entry into Instrument Meteorological Conditions

For the IIMC scenario Lake Ohrid was selected, with the rotorcraft initially flying south alongside the western bank of the lake at 100 KIAS at about 500 ft AGL. In this scenario, visibility would suddenly drop to zero when the helicopter passed a predetermined latitude. After this point, because of the closeness of mountains ashore the pilot was advised to make a left 180° turn to get out of the IMC condition. The flight would end after a certain amount of time had elapsed. IMC conditions would remain until the end of the flight.

The objectives to be tested in the IIMC scenario were:

- To evaluate the effectiveness of the visual enhancement concepts in terms of pilot acceptance, pilot workload, visual cues improvement and flight safety. Since the pilot's task involves the use of the indications given by the visual enhancement concepts in the flight control loop (e.g. maintaining altitude by using the enhanced visual cues) another item of the effectiveness are the rotorcraft's flying qualities.
- To determine to what extent those enhancement concepts, which depend on the hypothetical working of peripheral (or ambient) cues (viz. the Malcolm Horizon and the LED concept), are affected by the presence of a second crew member who might (possibly) interfere or block the view.

4.3 Controlled Flight Into Terrain

For the CFIT scenario the mountainous region near Peshkopi was selected because of its ridges, hills, etc. In the visual scenery the ground texture was furthermore removed almost completely and a layer of snow was added to give the impression of a snow-covered world with a misty underground. A cockpit view of the scenario is shown in Figure 7 where the mountain ridges can be faintly seen on the left. On this photo both the LED concept and the HUD Orange Peel are visible.

Figure 7 View from the cockpit in the CFIT scenario with the HUD Orange Peel and LED concept

The objectives to be tested in the CFIT scenario were:

- To evaluate the effectiveness of the visual enhancement as well as audio enhancement concepts in avoiding hazardous conditions, i.e. approaching terrain. This too is to be rated in terms of pilot acceptance, safety, situational awareness, etc.
- To evaluate the effectiveness of both a visual enhancement as well as an audio enhancement concept.

5 Simulation results

The results obtained in this project are presented in this chapter for each scenario (IIMC and CFIT) and includes for each concept the pilot acceptance, workload, handling qualities (only for the IIMC scenario), situational awareness, eye movements and safety. This latter is a combination of a computed Risk Factor (RF) and subjective ratings from the questionnaire. The RF takes into account the mean and standard deviation of height-above-ground h_R, airspeed IAS, rate of descent ROD, limits for roll (<90 deg) and pitch angles (<30 deg).

5.1 Results in IIMC scenario

The concepts tested in this scenario were, next to the baseline (none), all visual concepts (Malcolm horizon, Orange Peel and LED).

5.1.1 Pilot acceptance

The pilot gave concept acceptance ratings per run when flying with a concept. A histogram of acceptance ratings per concept is given in Figure 8. The LED concept was much less accepted ('just rejected') than the Malcolm Horizon ('just accepted') or the HUD Orange Peel ('fully accepted') for the IIMC scenario. Also for the LED concept there were 2 ratings with 'fully accepted', hence the pilots were not unanimous.

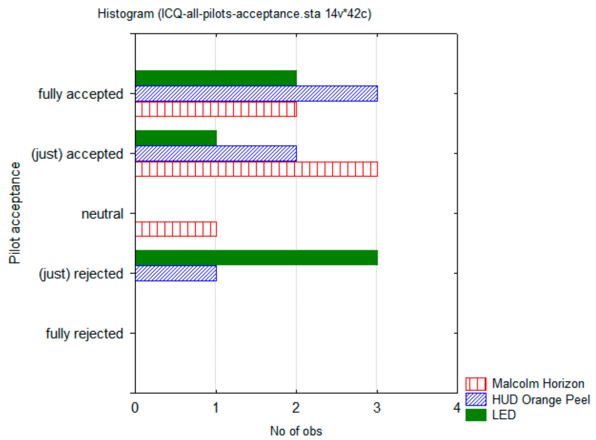


Figure 8 Pilot acceptance of IIMC enhancement concepts

5.1.2 Workload

The Malcolm Horizon required slightly less task workload in this IIMC scenario than the 'no concept' case. The other concepts had no statistically significantly lower workload than the 'no concept' case. The demand on the pilot was rated slightly lower for the baseline (none) than for the other concepts.

5.1.3 Handling qualities

The Cooper-Harper Rating (CHR) scale was used to rate flying qualities. Due to difference in familiarity with the scale the ratings of the EASA test pilot have been superimposed on the other CHR ratings, see Figure 9 (note that the test pilot did not fly all conditions).

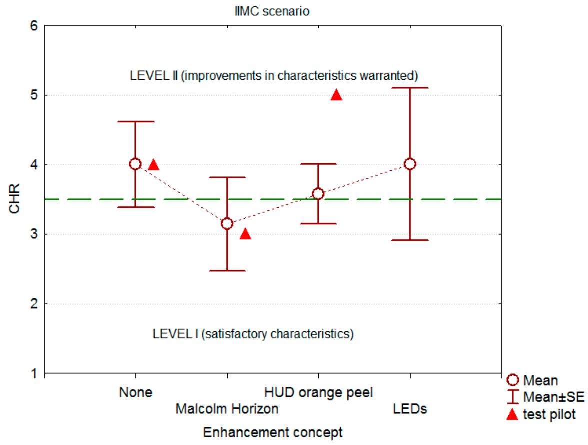


Figure 9 Cooper-Harper Ratings (CHR) per enhancement concept; IIMC scenario (lower is better)

The flying qualities improved (lower CHR) from Level II (improvements in rotorcraft characteristics warranted) for the 'no concept' case to Level I (satisfactory) when having the Malcolm Horizon on-board. This trend was also confirmed by the ratings of the test pilot (see triangles). Noteworthy is that for the HUD Orange Peel the test pilot scored a much higher (worse) CHR of 5 than the average value of about 3.5 for that concept from the other 6 pilots. The main reason was the test pilot's comment that this concept tended to PIO (Pilot-Induced Oscillation), which was not evident with the other concepts. The other non-test pilots did not notice this PIO tendency that clearly.

5.1.4 Situational awareness

Per concept a histogram of the ratings on situational awareness is shown in Figure 10. The enhancement concept did not have a statistically significant effect on the situational awareness for this scenario and on average varied widely for each concept, from excellent/good to poor/bad.

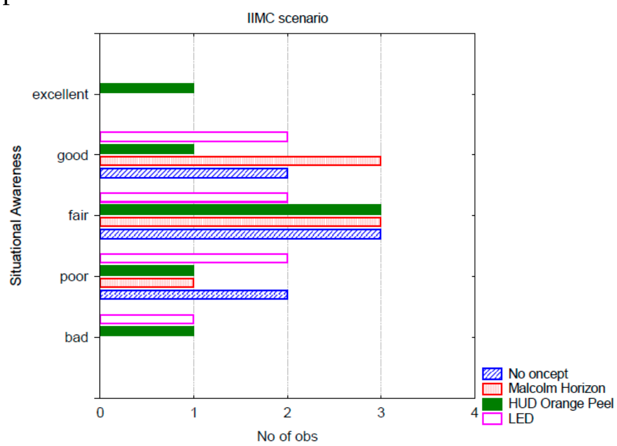


Figure 10 Situational awareness for IIMC enhancement concepts

5.1.5 Eye movements

The focal attention data for the IIMC scenario is summarised in Figure 11.

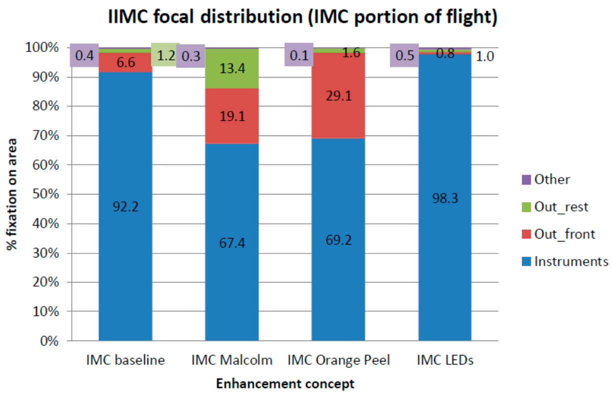


Figure 11 IIMC scenario summary of focal distribution of concepts (IMC segment of flight)

From this the following results are derived:

- The visual enhancement concepts drew more focal attention out front, and less on the instrument panel, except with the LED concept. This is as expected
- With the Malcolm Horizon also more attention was drawn to ‘Out_rest’, i.e. more outside but not in front of the pilot. This implies the pilot is also looking at the extremities of the MH line, which is also as expected
- With the LED concept practically no focal attention is given to the outside world, and almost complete focus is on the instrument panel, even more than with no concept, except a very small portion outside (1%) or out front (0.8%). Apparently pilots found nothing outside to look at with the LED concept, which is true. It is possible that the very small amount of focus outside could be related to the pilot looking at the front LED strip that was just behind the instrument panel

5.1.6 Safety

The visual enhancement concepts had no statistically significant effect on rated safety. The LED concept seemed to be rated somewhat more unsafe than the other concepts, but the differences are not statistically significant. Associated with safety is the number of crashes that occurred. During the simulations 2 crashes occurred. One crash occurred with ‘no concept’ and one occurred with the LED concept, both of which were typically a loss of control situation.

5.2 Results in CFIT scenario

The concepts tested in this scenario were, next to the baseline (none), the Orange Peel and HTAWS.

5.2.1 Pilot acceptance

A histogram of acceptance ratings per concept is given in Figure 12.For this scenario the HTAWS was accepted just a little bit less than the HUD Orange Peel, but there was no statistically significant difference. The one 'neutral' acceptance rating for the HTAWS was given because of an HTAWS missed alert that resulted in a "classic" CFIT.

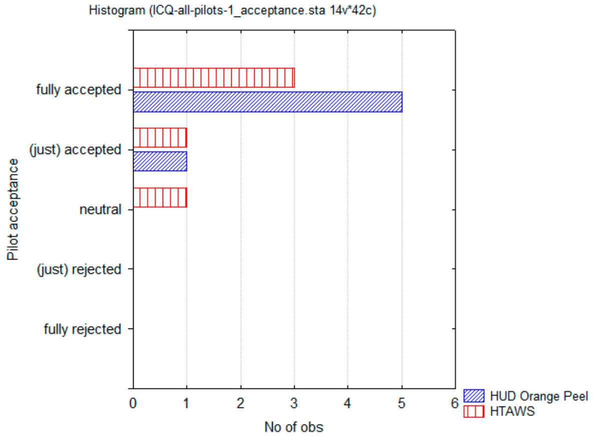


Figure 12 Pilot acceptance of CFIT enhancement concepts

5.2.2 Workload

The task workload did not differ statistically significantly between concepts, despite small differences. Also the demand-on-the-pilot did not differ between the concepts.

5.2.3 Situational awareness

Per concept a histogram of the ratings on situational awareness is shown in Figure 13. The Orange Peel had a better situational awareness (modal value 'good') than with 'no concept' (modal value between 'fair' and 'good'). Between the HTAWS and the 'no concept' there was not much (statistical) difference.

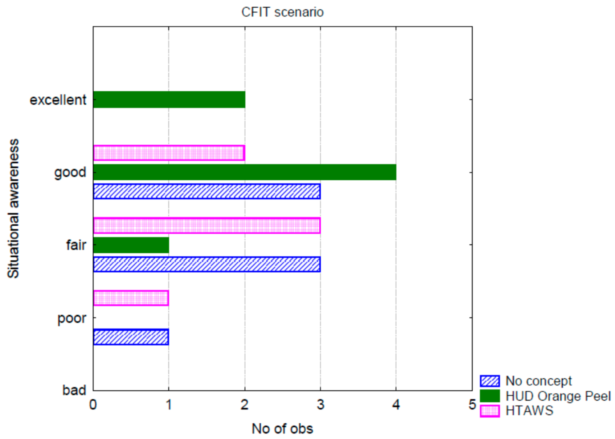


Figure 13 Situational awareness for CFIT enhancement concepts

Nevertheless, it was observed during the CFIT runs with the HTAWS that pilots tended to respond quite strongly to the alerts by increasing pitch angle in order to climb and so avoid imminent collision with the ground (hardly any collective inputs were given as the speed was deemed to be high enough).

5.2.4 Eye movements

The focal attention data for the CFIT scenario is summarised in Figure 14.

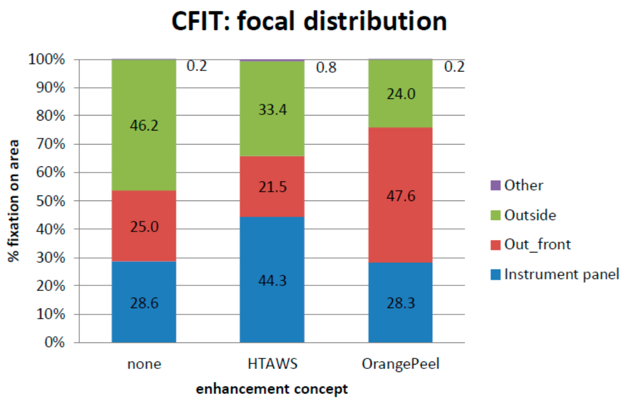


Figure 14 Focal distribution in the CFIT scenario for the enhancement concepts

From this the following results are derived:

- The time spent on the instrument panel for the HUD Orange Peel concept and baseline were the same (28%).
- With the HTAWS concept more time was spent on the instrument panel (41.3%) than with no concept (28.6%), at the expense of looking outside beyond the front region (33.4% instead of 46.2%). The HTAWS was expected to show the same visual behaviour as the baseline. However, the presence of a “guardian angel” (HTAWS) apparently reduced the need for scanning more outside for possible terrain or related obstacles. As one pilot put it, “HTAWS is very confidence building”.
- With the Orange Peel more time was spent on the area ‘Out_front’, in the baseline case more time was spent on ‘Out_rest’. That is, with no concept pilots looked around widely, while with the HOP they ‘reduced’ their overall outside scan, especially the outer edges, to look more at the Orange Peel symbology. This is because it attracts attention but also offers information (e.g. the ground bar with height information). The time spent watching the instrument panel is the same for both ‘no concept’ and the Orange Peel.

5.2.5 Safety

The enhancement concepts had a statistically significant ($p<0.05$) main effect on the subjective rated flight safety, which was due to the Orange Peel having been rated significantly safer than the baseline (‘no concept’). The feature of inherent “look ahead” in the HTAWS alerts was very assuring to the pilots and well appreciated. Unfortunately with the HTAWS one case of missed alert occurred, which promptly led to a “classic” CFIT: a controlled flight into terrain without the pilot noticing the closeness of the ground. This case was rated as ’unsafe’.

6 Practical steps for implementation

In the next paragraphs practical steps for implementation of the technical concepts are described for the design, certification, deployment, operations and training.

6.1 Design

The design of both the Malcolm Horizon and the HUD Orange Peel is not yet complete since additional features need to be added to the displays, as indicated with the recommendations. For the LED concept this applies even more strongly. The Malcolm Horzion and Orange Peel concepts have been around in the fixed-wing world for quite some years already, but have not found application yet in the rotary-wing world. Also in the automotive world much work is presently being done in the area of head-up displays, which may carry over to the rotary world. That is why the TRL values for these concepts are from 6 to 8, and even less for the LED concept (estimated TRL=4). To increase this to TRL=6 requires additional piloted simulator tests with the upgraded LED.

6.2 Certification

Before proving that the concept is “air worthy” the additional tests as recommended need to be carried out before the concepts are ready for airworthiness certification according to CS-27 (Small Rotorcraft). Since the visual and/or aural cueing concepts fall in the non-required category the certification needs to focus on possibly generating misleading information, rather than on fail-safe issues.

For the HUD Orange Peel it must be realized that a double system may have to be installed, for pilot and co-pilot alike, unless a single system can be made that is transferrable from one pilot to the other. With the Malcolm Horizon or the LED visual enhancement concepts a single system will do.

6.3 Deployment

Deployment of the concepts depends upon the maturity level and the TRL level they are at. Presently they are not mature enough to be installed already in small rotorcraft, as the recommendations have made clear.

It is important that the regulating authorities do not delay any further needed development work on these concepts, as they are presently entering the “electronic cockpit”. The problem is that most of these advanced features are all head-down displays because they have been developed at the level of the system supplier but not the rotorcraft designer. But helicopter manufacturers “are on the move” in the development of new, advanced integrated cockpits.

6.4 Operations

If the operator leaves the visual enhancement concept in the rotorcraft, and active when switching on power for example, it will be easier for pilots to understand and become familiar with the novel visual enhancement concept(s) implemented. The pilots must have been instructed that with this device the rotorcraft will still be certified for VFR use if so equipped before adding the enhancement concept. For the concept(s) to be eligible for night-time use a dimmer switch should be available to adjust the luminance of the displayed information.

6.5 Training

For the HUD Orange Peel it is felt that more training is required before the pilot will intuitively act upon the cues given than is the case with the Malcolm Horizon. However, when presenting the display all the time the aircraft is airborne the learning will be substantially reduced.

7 Key conclusions and recommendations

Within the limitations of the simulation set-up (e.g. fixed-base simulator, non-test pilots used, emulated rather than ‘real’ enhancement concepts, no cockpit windows onto which to project the imagery of some of the concepts), and in summary it is concluded that:

- The HUD Orange Peel was the best visual enhancement concept tested, in terms of Usable Cue Environment. The eye tracker data showed that the HUD Orange Peel in the CFIT scenario attracted focal attention of the pilot at the expense of looking more around outside. In a scenario with other traffic besides mountains this drawing attention away may be detrimental to safety. Also it should be improved to alleviate PIO by reducing the Orange Peel-to-pitch ratio in order to reduce the overall loop gain.

- The Malcolm Horizon was the second best visual enhancement concept in terms of Usable Cue Environment. It was simple to interpret and pilots were quick to understand what the line meant. The handling qualities ratings improved.
- The HTAWS audio concept was greatly appreciated. The pilot comments were very favourable, the Time-To-Impact that was used as a threshold was much appreciated by the pilots as a simple concept. The eye tracking data showed that with the HTAWS more time was spent looking at the instruments than with ‘no concept’ in the CFIT scenario, at the expense of looking widely outside. Apparently the system is such a “confidence builder” that pilots felt it was not necessary to look for terrain that much since they had the “guardian angel” (HTAWS) on board.
- The LED as currently implemented, i.e. with “static” lights indicating roll angle, etc., should be regarded as not suitable for application. The vertical rate-of-descent cues were appreciated, however. The working of peripheral cues did not materialize in the way it had been expected. There are ways to define better peripheral cueing mechanisms to improve the situation, e.g. by making the roll and pitch attitude cue not a steady-state cue but a moving one.
- Technically speaking all the concepts evaluated are feasible using additional (miniaturized) sensors such as an augmented GPS (i.e. a GPS augmented with a Satellite-Based Augmentation System, SBAS), AHRS and a terrain database. This type of equipment is already available or becoming available soon.

In the light of the conclusions drawn, the following (summarised) recommendations are made:

- A pitch reference could be added especially to the Orange Peel and, to a lesser extent, to the Malcolm Horizon.
- The HUD Orange Peel should be improved to alleviate PIO. The way to cure the PIO tendency is to reduce the Orange Peel-to-pitch ratio in order to reduce the overall loop gain. In the implementation in this experiment the orange peel would be complete for -30 degrees of pitch. This could be increased to eventually a minimum of -90 degrees. The exact amount can be established after a stability analysis and a limited piloted evaluation.
- In order to reduce the risk of loss of situational awareness, in the sense of being unaware of descending too fast, it is recommended to have at least the vertical descent rate cueing that came with the LED concept in the cockpit. It was a great awareness trigger and appreciated by the pilots.
- All concepts could act as a confidence builder, as was especially seen with the HTAWS concept. When any of these, or other, concepts are implemented it is highly recommended to combine its introduction with an awareness campaign to highlight that

the concerning concept is meant as an escape / prevention concept and specifically not to extend the operational limits.

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