Enhancing Mission Effectiveness in Contested Airspace and Degraded Visual Environments through Advanced Symbology

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***Abstract*—Low level, high speed tactical flights in Degraded Visual Environments are challenging for helicopters and multi-engined fixed wing aircraft. Normal visual cues that are present in Good Visual Environments are degraded or non existent. Proximity to the ground and obstructions create a high workload, high stress pilotage task. A Helmet Mounted Display used in combination with a head tracker enables synthetic cues and/or aircraft state symbology to be displayed on the degraded real world view as conformal information enabling the pilot to remain ”eyes out head up” at all times. This paper presents a user centred symbology design for a Helmet Mounted Display to meet Chinook pilots’ needs for Operations in Low Ambient Light. Preliminary studies sought to understand the Human Factor principles required for symbology design as well as pilots specific needs in low level high speed flights. 2D and 3D-conformal symbologies were designed and specified with substitute users. 2D symbology designs were implemented and integrated to a cockpit simulator for future assessment.**

***Index Terms*—Helmet Mounted Display, Symbology, Degraded Visual Environment, Situational Awareness, Rotary Wing Aircraft**

I. Introduction

A Degraded Visual Environment (DVE) is one of the most challenging and dangerous situations for helicopter pilots. Risks such as Controlled Flight Into Terrain (CFIT), collision with obstacles or spatial disorientation arise from this situation. The NATO Industrial Advisory Group (NIAG) final report [1] identifies different degraded environments. They can be natural (e.g. snow, rain, etc) and aircraft independent or aircraft induced. Figure 1 depicts such environments. Landing operations can induce DVEs by generating sand, dust or snow clouds (brownout and whiteout).

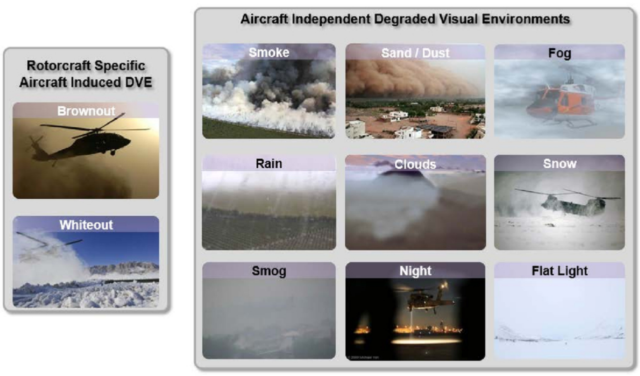

Fig. 1. Classification and identification of Degraded Visual Environments [1]

Surveillance and aircraft protection against external environment is a great concern. In particular, maintaining Situational Awareness (SA) during Low Ambient Light Operations (LALO) is a major issue. SA is commonly referred to as the correct perception of the current operational environment [2], ”knowing what’s happening”. In DVE conditions, SA and aircraft control cannot be maintained the same way as they are in normal Visual Meteorological Conditions (VMC) and may be lost.

The NIAG Final report [1] highlights six operational tasks in which DVE can significantly restrict rotorcraft operations: *maintain airspace situational awareness, hovering, taxi, take-off, landing, Nap of Earth (NoE)*. This paper focuses on the NoE task, which is a very low-altitude flight course used by military aircraft to avoid enemy detection and attack in a high-threat environment.

The aim of this work is to take a novel approach to the display of information to improve SA and reduce workload in high stress helicopter operations. The objective is to propose a solution based on symbology and draw on Human Factor (HF) principles. This solution links Head Down Displays (HDDs) and eyes-out displays to allow a better allocation of the tasks between the Handling Pilot (HP) and the Non Handling Pilot (NHP). This study was intended for a monocular Helmet Mounted Display (HMD) fully capable of displaying color imagery. The HMD uses a combination of Night Vision Goggles (NVGs) or a sensor image and colored symbols overlaid on the ”real world”. The system uses a Hybrid Optical-based Inertial Tracker integrated in the helmet for head tracking. This technology relies on ”fiducials” placed in the cockpit and allows a wide use of imagery. Thus the latter is not restricted to be to screen referenced and can be aircraft or earth referenced.

As display clutter is a major concern for pilots, the solution shall ensure a good trade off between the needed information and display clutter. This work concentrates on conformal symbology and an intuitive method for determining range from current aircraft position to the environment.

II. Background

A. Situation Awareness Concepts

I try to give to the reader a better understanding of Situation Awareness from the pilot perspective and its evolutions. SA is one of the most important terms of the subject and requires a definition. Although SA generally refers to ”knowing what’s happening”, several definitions have been proposed and are exposed in [3]. The main SA concepts are explained in the following sections.

1) Situational Awareness: Among the attempts to define SA, Endsleys work [4] is mostly cited. Endsley distinguishes the term Situation Awareness, as a state of knowledge, from the processes used to achieve that state, as acquiring or maintaining SA. She defines SA as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future". She presents a theoretical model of SA based on its role in dynamic human decision making depicted in figure 2. According to this model, the basis of SA is formed by the perception of relevant elements in the environment. A synthesis of these elements forms the comprehension of the current situation which is compared to the operators goals. The last level of SA is provided by the ability to project future states of the environment that are valuable for decision making. Numerous factors affect and influence SA. Among these factors, attention and working memory are presented as critical factors limiting operators from acquiring and interpreting information from the environment to form situation awareness. Mental models and goal-directed behavior are important for overcoming these limitations.

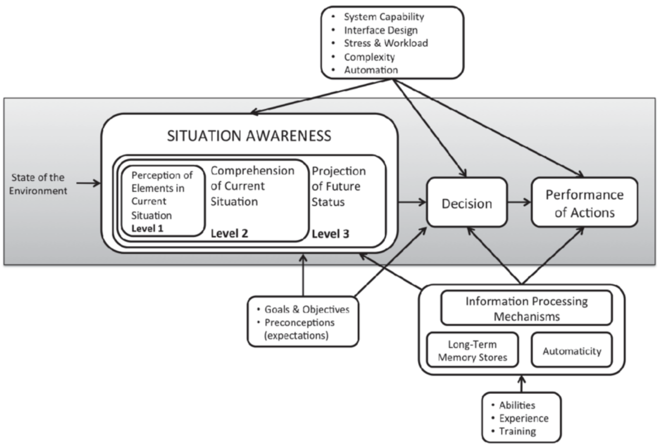

Fig. 2. Model of Situation awareness in dynamic decision making [4]

2) Team Situation Awareness: In many organizational environments, especially complicated ones, a team of individuals takes charge of the operational tasks [3]. The traditional and dominant view emphasizes Team SA on a shared understanding of the situation, that is, the team members should have a common picture. Endsley raised a Team SA model, in which a set of circles overlaps with each other [4]. Each circle represents a team members SA elements related to his or her specific role. The overlaps of the circles represent shared SA and the union of the circles represents Team SA. Team SA is defined as "the degree to which every team member possesses the SA required for his or her responsibilities" [4]. The success or failure of a team depends on the success or failure of each of its team members.

Salas et al [5] include team processes in their definition of Team SA. The limitation of ones mental model can be complemented and updated through the information exchange with other team members. Team processes, such as planning and assertiveness, facilitate the information exchange among team members.

3) Distributed Situation Awareness: Stanton et al [6] propose that SA is distributed amongst the humans and nonhuman artifacts in the socio-technical system. In their view of Distributed Situation Awareness, SA no longer exists solely in the individuals, but is an emergent property of the system. A system analysis cannot be accounted for by summing independent individual analyses. The basis of their theory is described in the following propositions:

- SA is held by both human and non-human agents. Technological artifacts (as well as human operators) have some level of situation awareness (at least in the sense that they are holders of contextually relevant information). This is particularly true as technologies are able to sense their environment and become more animate.
- Different agents have different views on the same scene. This draws on schema theory, suggesting that the role of past experience, memory, training and perspective. Animate technologies may be able to learn about their environment. The impact of technology on Distributed SA changes as a result of crew training and familiarization.
- Whether or not one agents SA overlaps with that of another depends on their respective goals. Different agents could actually representing different aspects of SA.
- Transactions (in the form of communications and interactions) between agents may have verbal and non-verbal behavior, customs, and practice (but this may pose problems for non-native system users). Technologies transact through sounds, signs, symbols and other aspects relating to their state.
- SA holds loosely coupled systems together. It is argued that without this coupling the systems performance may collapse. Dynamic changes in system coupling may lead to associated changes in Distributed SA.
- One agent may compensate for degradation in SA in another agent. This represents an aspect of the emergent behavior associated with complex systems.

Stanton [7] reports that the application of Distributed SA has led to encouraging results. It promotes higher performance in teams than shared SA. Distributed SA theory offers explanations of the behavior of complex socio-technical systems in a wide range of domains.

4) Synthesis: The definition of SA has changed over the past 25 years, from a SA focused on individuals to teams, then implying socio-technical systems [8]. Depending on the studied system, one should apply the model matching the scale of the studied system. For example, in aviation, one could study the awareness of the flying pilot and apply the Endsley's linear model. Other members of the crew could be implied, suggesting the use of a Team SA model. Flight instruments could be also included in a Distributed SA model. In a big picture, air traffic management and infrastructures are also involved. To describe SA in a military helicopter flying in

LALO conditions, I chose to use the Distributed SA model, implying the crew members as well as flight instruments.

B. *Eyes-out symbology for Helmet Mounted Display*

HMD symbology design is crucial as pilots are usually trained to keep constant visual contact with the outside world even with a poor visibility [9]. Hence staying eyes-out is essential, especially for pilots operating in very low altitudes or, in the military context, need to perform NoE missions. HMDs allow for an increased freedom in movements and provide the ability to view instrument information and outside scene simultaneously. However, the increasing amount of important information may result in display clutter and occlusion of the outside scene. This section exposes some symbology properties essential for eyes-out symbology design.

1) Frame of reference: There are three possible frames of reference for the display of information: the screen frame, the aircraft frame and the absolute geospatial frame [10]. The HMD allow off-boresight scanning, i.e. the imagery can be viewed independently of the heads orientation whereas with a Head Up Display (HUD), only boresight scanning is possible, i.e. present images along the heading vector of the aircraft. Moreover, real-time tracking of the pilots head movements enables a continuous display of imagery in the forward field of view adapting dynamically to the current head direction with the effect that the overlay remains spatially linked with the outside world (= world-referenced or conformal imagery) [11].

Information displayed on the screen frame are fixed whatever the pilots head position. The information displayed is generally 2D and refers to the aircraft and system states.

The aircraft frame can be seen as an enveloping world of virtual symbolic entities around the aircraft [12]. This frame is adapted for attitude indicator [10], sometimes referred to as a "virtual HUD". Placing this instrument only in the front view of the aircraft (displayed only when the pilot is looking in the longitudinal axis of the aircraft) avoids mental spatial rotations while the pilots head is orientated elsewhere. This frame can be used to replicate an instrument panel or virtual flight deck.

The geospatial frame is conformal to the outside world. Information (symbology) that is displayed in a geospatial reference frame can be overlaid on, or replace, information normally provided by the real world view. This is often referred to as 3D Conformal Symbology. The ability to accurately register such information depends on the systems ability to compute the positioning of symbology using knowledge of:

- Aircraft orientation and position in the geospatial frame of reference
- Head position with respect to the aircraft

2) Color coding: Most of HMDs in use are monochromatic. Differences in visualization use other visual variables such as brightness, shape or motion to distinguish between symbols. Color capable HMDs are in operation and development, adding a new visual variable to code information [10]. Concerning color choice, only a few studies have been conducted mostly due to scarcity of usable displays. Most studies concern chrominance contrast to discriminate symbology from the background. Only recent full-color HMDs can display blue with enough luminance to distinguish it from the environment (specifically a blue sky). In that very few studies analyzed the best color combinations and their use on a HMD. Most recommendations ([13], [14], [10]) encourage designers to choose only few colors, easily differentiable to structure and categorize the information. Primary colors and their complementary colors meet the discrimination requirement, provided a sufficient luminance is achievable[1].

3) Visual clutter: The increasing amount of important information may result in visual clutter, occulting the outside scene. It increases the search time to gather necessary information to accomplish a given task successfully and safely [15], [10]. The display design process is to ensure a good trade-off between the information needed and the display clutter [16]. The cost in clutter is the most crucial concern for pilots [10] and results in difficulties in selective and focused attention [11]. Staying eyes-out and being able to see the outside scene is essential for helicopter pilots in any circumstances.

4) Monocular / Biocular / Binocular considerations: HMDs can be classified as monocular, biocular and binocular [17]. Monocular means the HMD imagery is viewed by a single eye. Biocular means the HMD provides two visual images from a single sensor; each eye sees the same image from the same perspective. Binocular means the HMD provides two different perspectives of the object scene from two separate image sources (one for each eye).

a) Monocular issues: Monocular HMDs display the symbology to only one eye. They have a reduced Field of View (FoV) resulting in the need for increased head movements [17]. The use of a monocular HMD may cause a performance problem due to binocular rivalry. Binocular rivalry is a visual phenomenon that occurs when dissimilar monocular stimuli are presented to corresponding retinal locations of the two eyes. The two stimuli compete for perceptual dominance [12]. It causes viewing conflicts between the eye (usually the dominant eye) viewing the display imagery and the eye viewing the outside world. The two images cannot be successfully fused to form a coherent, single, image. The natural response of the visual system to such a situation is to suppress the visibility of all or part of one image. This suppression, however, usually shifts between both eyes producing alternating images [11]. Other issues such as rest vergence, inter-occular rivalry, retinal-rivalry and eye dominance are discussed in [12], [18], [17], [19] and [20].

b) Biocular / Binocular issues: Humans view scenes binocularly. Each eye sees a slightly different view which provides an apparent impression of depth in a 3D image (stereopsis) [17]. Biocular HMDs present the same image to both eyes and are not able to provide stereopsis. However with binocular devices, each eye sees a different image, which adds the benefit to provide stereopsis and partial overlap

[1]Chrominance and Luminance contrast contribute to adequate viewability.

to enlarge the horizontal FoV. Partial overlap consists of three regions, distinguished by how each stimulates the visual system (monocular left, binocular, monocular right) [12]. This can result in the fragmentation of the three regions in three separate areas. Misinterpretation, binocular rivalry may result and targets are less detectable in monocular regions. The fragmentation is supported by the binocular summation of the stimuli from the overlap area. It causes this to appear about 40% brighter than the monocular peripheries. Luning, which consists in darkening of the flanking monocular regions may occur [17] in non-fully overlapped systems.

C. Pilots visual perception and control strategies

The visualization of 3D conformal information on a HMD requires a fundamental understanding of the human visual perception and pilot's control strategies. This subsection provides a brief review of visual cueing.

1) Pilot visual perception: Gibson [21] describes an ecological approach to visual perception, in which perception relies directly on the information of external stimuli. He argues that the central function of perception is to facilitate interactions between the individual and the environment [22]. Gibson identifies the **optical flow** as the pattern of apparent motion of objects, surfaces, and edges in a visual scene caused by the relative motion between an observer and a scene. Figure 3 shows an example of optic flow while moving above the surface to the horizon. The point towards which the pilot is moving appears motionless, with the rest of the environment apparently moving away from that point. The relative rate of flow provides information about the ground surface. Global optical flow contributes to the perception on velocity and distances.

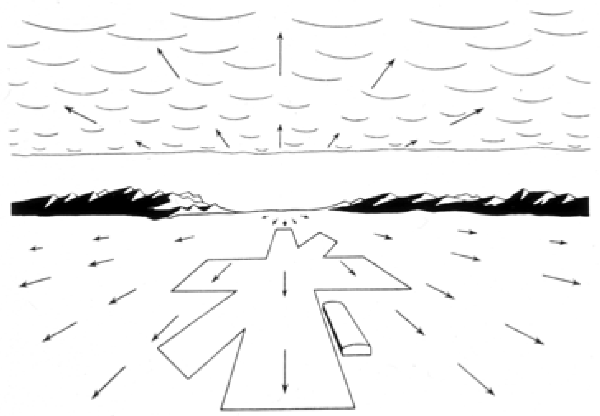

Fig. 3. Optical flow [21]

Lee [23] argues that the time-to-contact, or time to determine the moment at which there is going to be contact between the pilot and some object, can be worked out directly through the rate of change of the expansion of an object. Lee defines tau as the size of an objects retinal image divided by its rate of expansion. Tau specifies the time to contact with an approaching object. The faster the rate of expansion of the image, the less time there is to contact. The Tau-theory is in agreement with Gibson's ecological approach because information about the rate of expansion is directly available from optic flow. Relying on the work of Perrone [24], Padfield [25], with Clark [26] proposed a usable flow region where pilots pick the optical flow and Tau to ensure a safe flight. They place this region at a distance between 12 and 15 or 16 eye-heights, corresponding to about 6-8 seconds look-ahead times, see figure 4.

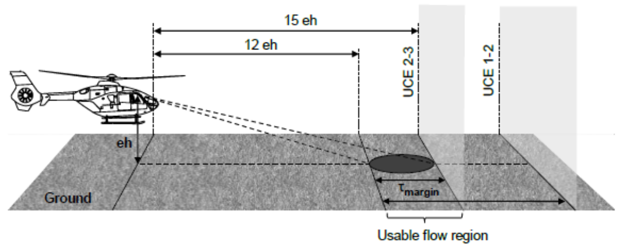

Fig. 4. Usable optical flow region [25]

Basic principles of depth perception can be found in [10], [18], [22]. Depth can be perceived through oculomotor/binocular cues or monocular cues. The first originate from our visual system and are more relevant at close distances (convergence, accommodation and binocular disparity). The second are more relevant for the task of helicopter flying in DVE. Motion parallax (moving objects farther away appear to have less relative motion than objects closer to the viewer) and occlusion (close objects obscure parts of distant ones) are among the most effective depth cues.

2) Pilot control strategies: Padfield [25] describes flight control as a combination of short term closed-loop guidance and stabilization and longer term navigation as illustrated in figure 5. Stabilization is the short term task of attitude control, guidance is the mid term control of flight path. The long term task is the navigation to control the whole course of the flight. In accordance with Padfield's model, Mettler et al [27] propose a hierarchical multi-loop model of human guidance behavior across planning, perceptual guidance and motor control levels. The top level performs the planning based on the decomposition of the task and environment, and codifies the plan of a sub-goal sequence. Perceptual guidance level adopts interaction pattern to close the motion gap to the reference defined by the currently active sub-goal. At the lowest level, a compensatory tracking system implements the desired motion for the aircraft. However this task is markedly affected by the automatic stabilization mechanisms that are implemented in the aircraft.

Rasmussen [28] propose three level of human behavior with regard to human performance. A skill-based behavior represents a type of behavior that requires very little or no conscious control to perform or execute an action. A rule-based behavior is an application of stored rules or subroutines in a familiar situation. The knowledge-based behavior is engaged to manage unfamiliar situations which require a tain amount of workload. The less effort it takes, the more resources can be spent on achieving SA.

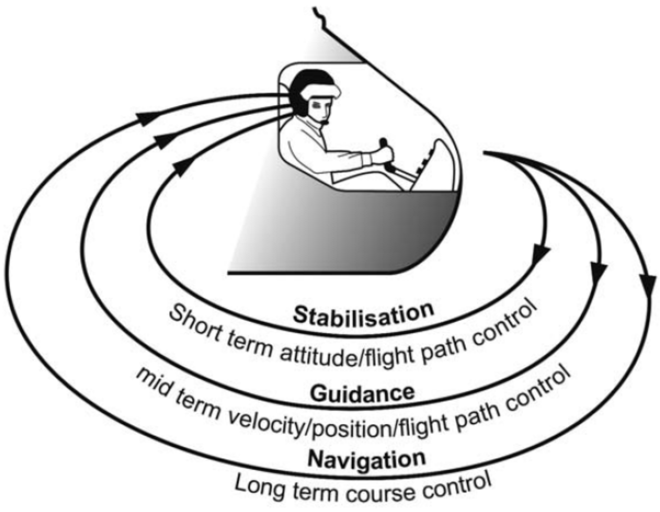

Fig. 5. The three functions of flight management and control [25]

higher conceptual level. Hourlier [29] and Csikszentmihalyi [30] relate cognitive investment (or abilities) to the cognitive load (or challenges). A feeling of increased mental workload appears if we sense that the constraints (demands from the situation or lack of time) overflow the amount of resources we think we can mobilize. When the demand from the environment is very low (thus needing very little resources to deal with) we have a feeling of boredom that is also hard to maintain.

In practice, pilots have to deal with guidance and stabilization and, in slower time, navigation [25]. In addition, control augmentation systems have been developed to assist the pilot in DVE, especially for the task of stabilization. Thus, stabilization is not required by the pilot and attention can be focused on other tasks, e.g. to remain situation awareness and to search for obstacles [15]. Four types of control mechanisms are related to human control theory [10] and are involved in the pilots control strategies:

- **Preview/Prospective**: The whole course or trend of the parameter to be tracked is displayed (e.g. highway in the sky)
- **Predictive**: The future state of a parameter is anticipated through the display (e.g. a flight path marker which allows to see the aircraft position a few seconds ahead)
- **Pursuit**: A command value is displayed (e.g. a follow me aircraft) which should be followed
- **Compensatory**: The error of a parameter to be tracked is displayed (e.g. airspeed error)

Compensatory strategy (or differential perception) is a low workload process which allows realizing precise tasks.

3) Synthesis: To ensure a safe flight and to perform the obstacle avoidance task, pilots rely on the global optical flow field provided by the environment. Time-to-contact or Tau emerges from this flow and supports a predictive control strategy used for flight guidance. Pilots use different control mechanisms to control the aircraft. This task requires a certain amount of workload. The less effort it takes, the more resources can be spent on achieving SA.

III. Pilot's tasks and needs capture

The objective of this work is to propose symbology designs to support the LALO task. Following a user centered requirement capture and design process, pilots' specific needs for NoE flights have been captured. Sound HF principles and knowledge elicitation from substitute users and HF experts has been used throughout this process. The specific tasks are then described.

A. System definition and substitute users

The primary need for the study is that the symbology should increase terrain awareness and aircraft state awareness to a Chinook crew. The final users are identified as military helicopter pilots, especially the HP and the NHP. However the system boundary to study is wider. As mentioned in section II-A, SA is held by human and non-human agents. It implies the Flight Instruments (Head Down Displays, eyes out displays and pilots' control inputs), the sensors (Forward Looking Infrared (FLIR) and NVGs) as well as the interactions between the different agents, including other crew members, all contribute to SA. Figure 6 depicts the system boundaries.

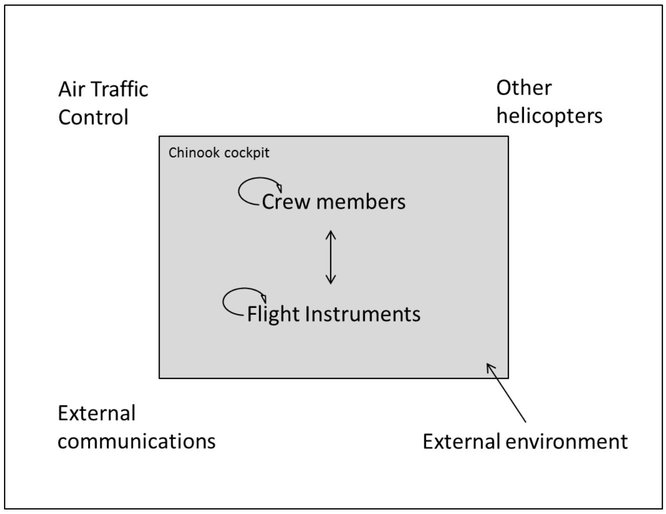

Fig. 6. System Boundaries

I did not have access to the final users for the need requirement or the task analysis. However, three pilots working in Thales Avionics (in the UK, in France and in Australia) were available to share their experience. Furthermore, two HF experts brought their knowledge to the project as well as a Chinook cockpit expert. Needs were captured with these substitute users. Thales HF engineers had previously captured the needs for LALO in a previous classified program.

B. Piloting tasks analysis

As defined by Padfield [25], the primary task of flying the aircraft can be divided in three subtasks: stabilization, guidance and navigation [25]. In addition, secondary tasks such as system monitoring are conducted in less demanding flight phases, see figure 7.

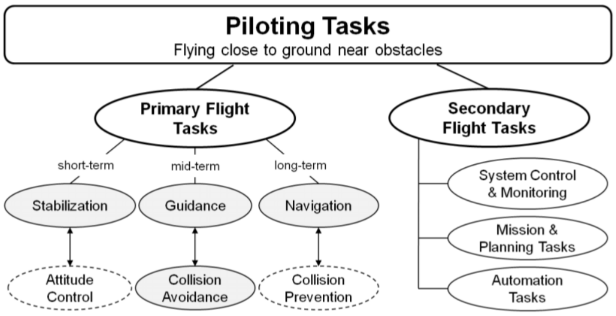

Fig. 7. Piloting tasks [10]

The analysis focused on the primary task of flying the helicopter, more demanding in DVE conditions than secondary flight tasks. For each sub-task, a set of information are required by pilots to perform the task. Table I, adapted from Viertler thesis [15], summarizes these information with examples from 2D and 3D conventional head up symbology. The examples provided are not exhaustive.

In DVE, identifying obstacles is not only a constraint but also an important task for maintaining SA while flying at low altitude. The ecological approach of visual perception [21] defines a usable flow region between 12 and 16 eye-heights in front of the aircraft. Visual information provided by this zone is essential for a collision-free flight.

C. Low Ambient Light Operations

The LALO task consists in a tactical high speed low level flight. Due to very low light levels during LALO, crew NVGs are not able to provide the visual references required for the pilot to maintain terrain/obstacle clearance or contour flight without additional assistance. External light levels are insufficient to provide a compelling image of the external scene, even using the best Image Intensifier (I^2) technology. The primary source of pilotage information is the FLIR image. This image is displayed on the HDDs.

Chinook flight operation currently involves three people. The HP ensure the stabilization task. Vertical flight path guidance is achieved via voiced commands from the NHP to HP, from interpretation of information provided by the cockpit displays. Horizontal guidance is provided by a conventional moving map. This was described as Terrain Following Radar at the human level. Navigational duties on LALO are conducted by a crewman who navigates using the crewman workstation.

The workload associated with NHP LALO terrain avoidance task is very high. The most demanding task is to blend information from three sources: the FLIR, a 2D Map and the NVG image. A three-years study [31] was conducted in France in the early 2000's following complaints of headaches and inability to perform long NoE helicopter night flights. This study revealed a sometime critical visual load due to a poorly integrated interface. The multiplication of points of view and sensors is extremely demanding on cognitive resources for the building of a coherent individual and collective SA.

As mentioned in section II-A, the SA model used is the Distributed SA model, applied to the Chinook cockpit, comprising pilots, crewmen, flight instruments and sensors. Each agent has its own view of the situation. Pilots face multiples representations of a given situation. They must be able to decipher each type of information but also establish links between these representations into a coherent whole. This cognitive fusion requires high workload because each representation has its own particularities in term of contrast, color, definition, field of view and information represented. Transactions of SA between pilots are mainly realized through aural description of the situation. Pilots deal with multiple information sources of more or less luminance and distant from the eyes resulting in costly perceptive transitions. They construct multiple mental representations (memory image, NVG vision, thermal vision[2], 2D map vision, verbal) which require a high cognitive integration.

To improve the NHP's ability to blend information from the different sensors, and reduce workload with the avoidance task, cockpit integration shall follow the cognitive continuity principle. This principle associates points of reference between different representations:

- Common cues between the displays. The pilot must be able to immediately recognize the similarities to establish a link between the representations.
- Continuous change of representation. A continuous and smooth transition between two representations allows the pilot to follow the transformation of the image of one object in one frame to its image in another frame.

IV. Symbology iterative design

A. 3D conformal symbology design and justification

The aim of this work is to propose a new symbology set to meet the users needs previously captured. Following the cognitive continuity principle, this symbology would overlay the FLIR image and would be displayed on the HMD. This would create links between the different head down representations and HP / NHP representations of the situation. The symbology was designed to provide pilot needed information to improve SA while reducing display clutter. The symbology presented is the final design, resulting from several short iterations. This phase implied substitute users in small focus groups. Prototypes were then presented to substitute users to gather informal feedback.

1) Distances definition: The global optical flow field provides information about speed, height, distances and turns. Studies, see chapter II-C1, established a usable flow region between 12 and 16 eye heights, reached in 6 to 8 seconds. Symbology must preserve and enhance it. It is worth noticing that the operational LALO procedure corresponds to a speed of about 2 eye-heights per second, similar to the speed used in

[2]An I^2 technology is natural whereas a FLIR image is unnatural as it is operating outside the normal visible wavebands.

TABLE I

REQUIRED INFORMATION FOR THE PRIMARY FLYING TASKS, ADAPTED FROM [15]

Primary flight task	Required parameters	2D symbology examples	3D symbology examples
Stabilization	Pitch and roll angle/rate, torque, rotor speed	Attitude indicator: pitch ladder, roll indicator, Arc Segmented Attitude Reference (ASAR), Torque bar	World aligned horizon
Guidance	Air, ground, vertical speed and rate, Barometric and radar altitude, Heading / rate	Primary flight display: airspeed, altitude and heading tapes, vertical speed bar, digital ground speed, radar altimeter	Optical-flow-field from terrain, Tunnel-in-the-sky, Ground referenced Flight Path Markers
Navigation	Waypoints, distance to go, time to go, estimated time of arrival	Digital moving map, horizontal, vertical flight profile	Ground referenced waypoints and flightpath

studies [25], [26]. In these studies, pilots were given a height and chose empirically a speed to ensure a safe flight. In that, a low altitude procedure implying a speed faster than 2 or 3 eye heights per seconds would be unrealistic. In addition, pilots use the usable flow region to perceive, understand the situation and to project their actions into the near term future to ensure a safe flight. Padfield [26] suggests a minimum temporal envelope of about 6 seconds for safe flight for low speed maneuvering. Before that, pilots have not the time to succeed "comfortably" the avoidance task. This highlights a minimal required SA for safe flight, giving a more precise definition of short term SA.

When considering the NHP terrain avoidance task, the mid term / guidance SA needs to be preserved. Pilots interviews empirically established a upper bound of a 30 seconds flight distance (1 nautical mile at 120 kts). Beyond this distance, visual cues are used for the navigational task, defining the long term SA. The delimitation between mid term and long term SA should be determined through pilots evaluations.

External visual cues are extremely important for short and mid term SA. The proposed symbology shall support it and enhance pilots perception. For this I determined three zones, depicted in figure 8:

- Zone 1 refers to the visible outside world scene. Relative to the aircraft, this zone extends from 0m to the visibility distance d_1.
- Zone 2 refers to the area where, in DVE conditions, the pilot only gets poor visual cues. It corresponds to the area where the visual cues, in Good Visual Environment, would normally support pilots tasks but, in DVE, are not provided. Zone 2 extends from d_1 to the upper bound d_2 of mid term SA.
- Zone 3 represents the area beyond d_2. The external visual cues are not used by the pilot for short and mid-term flight control.

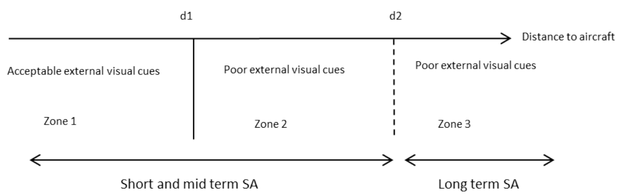

Fig. 8. Zones delimitation

2) Terrain representation: The terrain representation must enhance reality to provide the needed optical flow field while minimizing display clutter. Several techniques can be used. Slope break describes intensity of shading that is proportional to the terrain gradient, resulting in the higher magnitude of occlusion. Grids overlay the terrain to highlight its shape and provide very useful depth cues for guidance. Finally, contour lines or crests have a minimal clutter cost but provide valuable terrain avoidance cues i.e. "safety lines". They refer to the terrain highlighting at the line of zero rate of change of gradient.

I used a combination of the different techniques to preserve external visual cues, enhancing reality when these cues are missing and minimizing display clutter. Each Zone previously delimited has its own representation of the terrain. In the Zone 1, external cues are predominant and must not be hidden by symbology. Contour lines or crests are used for the terrain representation in Zone 1. In Zone 2, external cues are missing. To recover useful depth cues of linear perspective and compression for control and guidance tasks, a combination of grid and slope break is used. To reduce display clutter, in Zone 3, grid and slope break switch to display of contour lines or crests, which adds cues about the far field terrain surface. Figure 9 depicts the terrain representation concept.

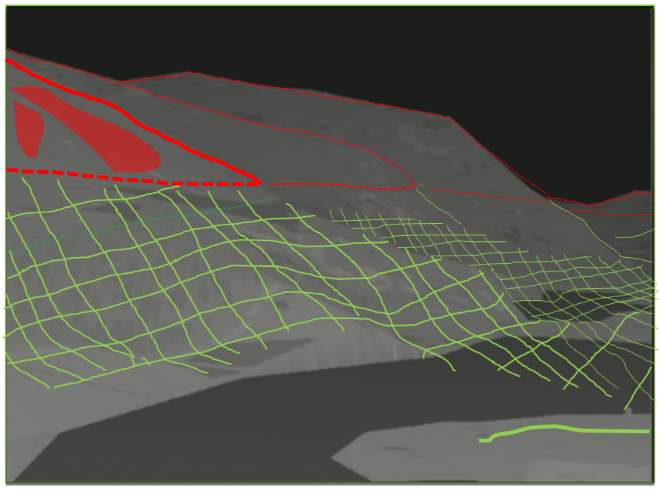

Fig. 9. Concept of terrain representation

3) Time/range and navigation information: One of the major pilots requirements is to be able to estimate precise obstacle distances from aircraft. They currently assess distances with fixed markers on the FLIR display[3]. Conducted interviews showed that pilots used distance information to estimate the time-to-contact. To improve NHP's ability to assess range and time-to-contact from the FLIR image and the imagery displayed eyes-out, three conformal rings are displayed in the aircraft frame of reference, see Figure 10. They represent the potential position of the aircraft 10, 20 and 30 seconds ahead. We are not good at evaluating absolute distance but given a certain metric it is possible to estimate its half or its double. Pilots can assess distances between features on the ground and rings acting as landmarks. As rings represent time information it is assumed that workload associated with obstacle identification, verbal communication and future action projection would be reduced. Furthermore, rings are linked to the aircraft speed so an obstacle identified between two circles would produce the same feeling of time to contact whatever the aircraft speed. Time rings should also appear on the 2D map to facilitate transitions between terrain abstractions presented on different displays. Time rings shift to distance rings to cater for low speeds.

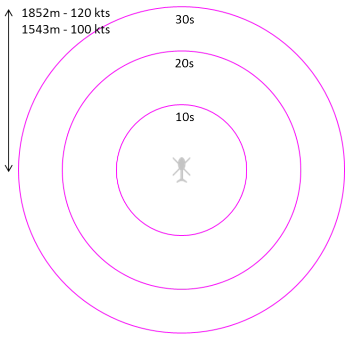

Fig. 10. Concept of conformal time rings

Pilots do not require precise flight path guidance for NoE flights as it is for an Instrument Landing System (ILS) approach [10]. They must be able to accomplish the obstacle avoidance task. Precise flight path guidance such as tunnels in the sky capture pilots' attention at the expense of obstacle recognition. To establish a good trade off between display clutter, attention capturing and flight guidance precision, I chose to use true conformal arrows displayed on the ground giving a preview and awareness of the *general* flight path.

B. 2D symbology design and justification

I followed the recommendation of positioning fixed symbols in a field of view of 15 degrees to minimize eye excursion [18] and thus reduce fatigue. I used a 15 degrees circle for flight instruments symbology, letting the most attention capturing part of the display (the center) free of fixed symbology. Colors were used to discriminate screen fixed symbology (in white) from aircraft frame symbology (in magenta). Figure 11 depicts the final 2D symbology prototype.

[3]This task requires a very high degree of training and re-training to achieve at the desired level of accuracy.

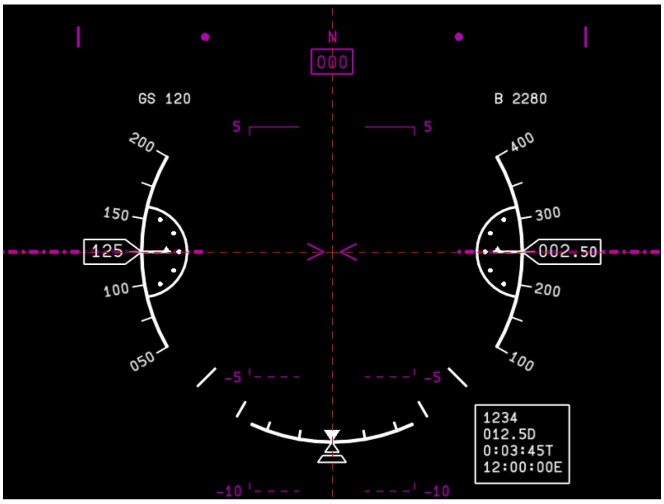

Fig. 11. Final 2D symbology prototype

A study of tools and technologies used for symbology prototyping established that I could only set up a development environment to implement 2D aircraft state symbology. 3D implementation requires a challenging technology that cannot be matured within a six month internship. The implemented solution is intended for a computer that will then send a video input to the HMD.

2D symbology was implemented for a computer target that overlays the FLIR image on HDDs and the natural head up vision. A tool providing a solution to both prototyping and development needs of embedded display specifications was used to create and design a graphical specification from both a static and dynamic point of view. The integration into the target used the generated code. A model describing the symbology behavior was implemented, handling aircraft and head tracking inputs.

C. Prototypes assessment

Several assessments of small design components occurred within short iterations. Furthermore, two aural presentations of the whole symbology concept were conducted. These presentations involved substitute users but also system engineers and technical directors. Prototypes were Powerpoint images and only represented a symbology concept, not behavior. Only a few properties could be evaluated with low fidelity prototypes and I carried out heuristic evaluations based on the following:

- Clear objectives: system objectives should be clear. The system should satisfy users expectations.
- Distributed attention: the system should facilitate the user task while not capturing the attention.
- Display clutter: the system should minimize display clutter.
- Human limitations: the system should not overload the users cognitive, visual, auditory, tactile, or motor limits.

I captured valuable feedback to iterate the prototype designs. The first and most important point was that users needed to see concepts animated to determine what they think would work.

Distance delimitations seem to be coherent. One of the greatest concern about time rings is that pilots are trained to perceive distances and think distances. To present time information could lead to false assumptions. Whether rings should represent time or distance information should be assessed through pilots evaluations on an implemented prototype.

V. Conclusion

The aim of this work was to design symbology based on proven HF principles to improve rotorcraft pilots' SA in DVE. I investigated SA and chose a Distributed SA model implying crew members and flight instruments to describe SA in a Chinook cockpit. Designing symbology for HMDs raised the issue of trade-offs between needed information and display clutter. Methods reducing display clutter such as frames of reference and color coding were applied. Pilot's perception was studied through Gibson's ecological approach, defining a usable flow region. Time-to-contact emerges from this flow and supports a predictive control strategy used for flight guidance.

To meet the LALO requirements I captured users needs with pilots and Human Factor experts. They identified that the multiplication of points of view and sensors are extremely demanding on cognitive resources for the building of a coherent individual and collective SA. I used a user centered process involving substitute users to design symbology bringing pilots a better SA, and improving the ability to assess distances and time. I implemented the 2D aircraft state symbology, defining the graphical specification which was then integrated on the cockpit simulator.

Quantitative assessments of the implemented symbology involving pilots should be performed. Evaluations will confirm parameters established in the symbology conception and will bring valuable feedback. Additional studies should be conducted on obstacle symbology, threat avoidance and Point of Interest cueing. Moding, (or displaying only the "right information at the right time") should be considered, involving a symbology display consistent with the flight phase and offering different levels of declutter. Thus pilot's interactions possibilities, especially with Hands on Collective and Stick, buttons and touch screens, should be studied.

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