ANALYZING VISUAL CLUTTER OF 3D-CONFORMAL HMD SOLUTIONS FOR ROTORCRAFT PILOTS IN DEGRADED VISUAL ENVIRONMENT

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Abstract

The increasing maturity of head-tracked optical see-through Head-Mounted Displays (HMDs) for pilot assistance in Degraded Visual Environments (DVE) enables a 3D-conformal presentation of well developed flight guidance parameters, added by scenery content for collision avoidance. With more and more information displayed on the HMD, the challenge of preventing visual clutter grows. In this paper, visual clutter will be analyzed and derived concepts for reducing clutter will be discussed. Additionally, extensions and tailored modifications of the Rotorcraft Simulation Environment (ROSIE) at the Institute of Helicopter Technology for enhanced future pilot evaluations of such HMD-DVE solutions will be described.

1. INTRODUCTION

To cope with the challenge of extending the helicopter flight envelope to degraded visual conditions under Visual Flight Rules (VFR) in uncontrolled airspace, while increasing safety at the same time, advanced visual systems are under investigation [1], [2]. These pilot assistance systems augment the visual environment by using information available from databases, imaging and ranging sensors, or other information sources.
Primary flight information for the piloting task of stabilization, guidance and navigation, together with terrain and obstacle information for collision avoidance, can be presented with a head-tracked optical see-through binocular display. Dependent on the nature of the displayed information, it can be presented in 2D or 3D-conformal manner and for an intuitive perception in different frames of references, i.e. head-fixed, aircraft-fixed or geospatial-referenced [3], [4].
While flight guidance parameter visualizations, like landing zone or highway-in-the-sky displays, are proven to return valuable feedback to the pilot, collision avoidance visualization is lacking in evidence to be well designed to support the pilot efficiently and to be safe enough for flying in degraded visual environments and obstacle proximity.
The increasing amount of important information may result in display clutter and occlusion of the outside visual cues. To derive improvements for existing DVE solutions, regarding the human-machine-interface, methods for analyzing visual clutter have been explored. Fig. 1 exemplary shows a basic implementation of 3D-conformal synthetic cues, simulated in ROSIE, with terrain and obstacle visualization to augment the outside visual cues for flight guidance and collision avoidance in severe visibility conditions. It represents the view of the pilot, see Fig. 2, looking through the HMD onto the virtual background of the simulation environment.
This work focuses on two strongly influencing sources, which lead to visual clutter for pilots when see-through HMDs are in use. The first source of visual clutter emerges from displaying too many

Fig. 1: Visual augmentation of the outside cues in ROSIE looking through the HMD (visual range 400 m)

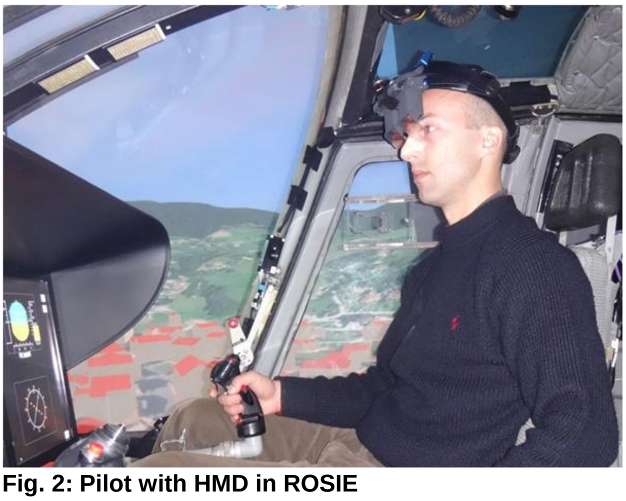

Fig. 2: Pilot with HMD in ROSIE

parameters or entities simultaneously, while the multitasking capability of the pilot is limited in the mental demand. Therefore the piloting task of flying is elaborated in more detail.

The second source of visual clutter results from display design properties and particularly the occlusion through luminous pixels in front of the real world view or the synthetic generated outside visual cues in simulation. Due to the limited field-of-view (FoV) of most HMDs, the central or even focal FoV of the pilot is used and thus, can be blocked adversely, which can lead to a degradation of task performance.

The next section breaks down the piloting task of flying to derive improved display concepts and to link visual entities to information required by subtasks. It also states pilot control strategies for collision avoidance briefly. Afterwards, section 3 explains display properties, which describe and affect visual clutter in the context of 3D-conformal synthetic HMD visualizations. In section 4, the method of active pixel ratio measurement, to determine the occlusion of see-through displays, is demonstrated with some variants in obstacle visualization. This functionality can be used as an engineering tool to reduce the occlusion in this augmented reality application. Finally, in section 5, the rotorcraft simulation environment (ROSIE) is described for enhanced evaluations of 3D-conformal display concepts through pilot-in-the-loop simulations.

2. PILOTING TASK ANALYSIS

Flying with very limited outside visual cues below visual ranges of 800 m close to ground in obstacle proximity and unknown landing sites requires good handling qualities and additional control assistance is very important. Augmented visual cues heads-up are the only mean to provide the pilot enough information to maintain situation awareness and to fly the helicopter manually. This is required to fulfill the desired mission and to make proper decisions in complex situations, where automation systems are limited in their assistance capability yet.

The piloting task can be divided into the primary task of flying the rotorcraft and secondary tasks, see Fig. 3. The latter include subtasks, e.g. system monitoring, planning and flight management tasks. The primary task of flying the rotorcraft can be further broken down into three major subtasks. According to Padfield [5], these are 1) stabilization, which is a permanent task of controlling the attitude of the rotorcraft, 2) guidance, which is the mid-term task to control the trajectory, like maintaining altitude or course over a period of more than a few seconds and finally 3) navigation, which represents the long-term task of finding the way from a starting point to a desired destination.

Identifying obstacles for a collision-free flight path is usually considered as a constraint, but it also requires mental resources of the pilot to maintain situation awareness and to avoid collisions with terrain and obstacles. Thus, three corresponding subtasks are added representing "attitude perception" for stabilization, "collision avoidance" for guidance in degraded visual conditions and "collision prevention" for navigating on less hazardous flight paths in DVE. For landing and hover situations, attitude and drift control is more important and has a strong effect on pilot workload, while in low-level flight and approach situations, collision avoidance and environmental situation awareness becomes very challenging in DVE. Finally, all tasks require the attention of the pilot. With sequentially allocated attention to all the tasks, the information accumulated therein contributes to maintain the overall situation awareness of the pilot.

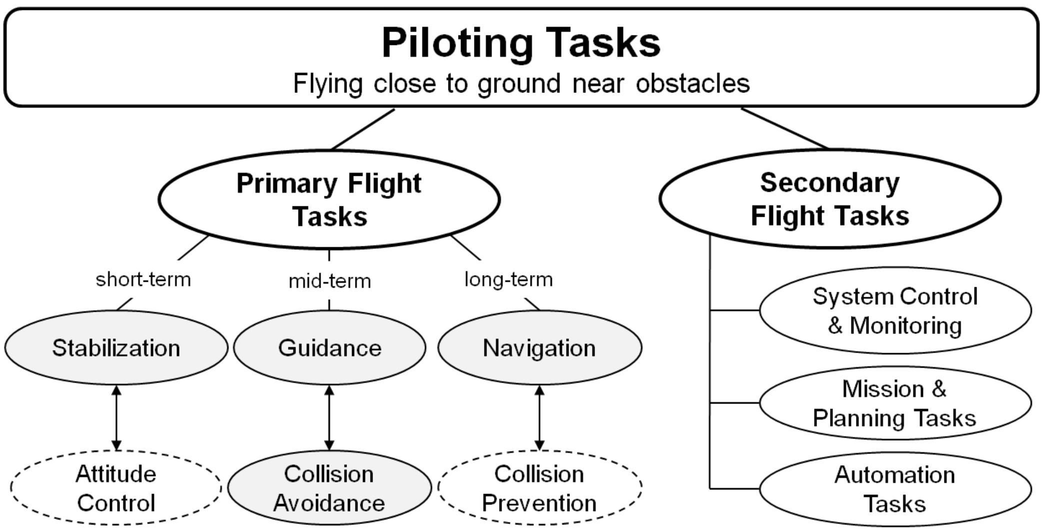

Fig. 3: Breakdown of the piloting task

2.1. Stabilization, Guidance and Navigation

Considering existing means for stabilization, guidance and navigation, the following prevalent information displays can be listed, which are usually presented in two dimensional head-down displays at the moment:

- primary flight display
- navigation display with horizontal situation indicator
- digital moving maps
- flight management systems

Including latest developments in HMD visualization concepts [6]-[8], not everything is presented in three dimensions. One reason therefore is, that 3D-conformal visualizations require a highly accurate head-tracking and helicopter position determination system. Another reason is, that some rotorcraft state information needs to be perceived precisely in a numerical way. Thus, two dimensional information is still meaningful and can hardly be replaced completely with a 3D-conformal counterpart in the real world. But some 3D-conformal features have become widely accepted as very valuable for stabilization, guidance and navigation:

- highway- or tunnel-in-the-sky
- 3D-conformal navigation markers on ground
- landing zone reference markers and symbols

Navigation markers overlaid onto synthetic terrain visualizations are useful in situations, which require no highly accurate tracking of the flight path, as it would be necessary for an Instrument Landing System (ILS) approach for example. Markers on the ground in form of an arrow or a triangle do not capture as much attention as a highway-in-the-sky, but still show a flight path head-up in addition to the route presented on a digital map head-down [9]-[11]. This helps maximizing the time spent looking outside searching for obstacles in the flight path. In helicopter scenarios with unknown landing sites, usually no external guidance or navigation infrastructure exists, which could provide information for generating a tunnel presenting the optimal approach path. Hence, navigation markers on the ground are of beneficial assistance in finding the landing site.

2.2. Collision Detection and Avoidance

For the subtask of collision avoidance, alike the subtasks before, two dimensional head-down-displays for assistance already exist. Static obstacles can be presented on the digital map. Helicopter Terrain Awareness and Warning Systems (HTAWS) color terrain information on displays, using elevation databases to identify mountains higher than the current helicopter altitude. Moving obstacles, e.g. other air traffic, can be included in the horizontal situation indicator with a corresponding flight path vector and velocity information.

Information about static and dynamic obstacles has been converted into 3D-conformal objects, for example highlighting other aircrafts with circles or rectangles [12]-[13]. Synthetic terrain imagery visualizations have been examined over the last decades, since the FoV for HMDs has increased and computational power for graphics rendering has improved. Different concepts, like a mesh representation or points with ridgelines, have been analyzed for increased situation awareness [14]-[17]. Furthermore, databases can be used to show detailed information about obstacles close to the helicopter requiring the attention of the pilot. These databases, even if updated frequently, cannot include every obstacle in the real world. Thus, ranging or imaging sensors will be required to close that gap and to provide enough near-field information for a safe flight.

Besides studying well established display concepts, it is important to consider the control strategies of the pilot behind such concepts, compared to the flight with natural references in good visual environments. Generally, four types of control strategies are related to human control theory [18] with display input:

- **compensatory**: The error of a parameter to be tracked is displayed, e.g. deviation to localizer or glide slope.
- **pursuit**: A command value is displayed, e.g. a flight director, which should be followed.
- **preview / prospective**: The whole course or trend of the parameter to be tracked is displayed, e.g. a tunnel-in-the-sky, which provides a preview of the flight path.
- **predictive**: The future state of a parameter is anticipated through the display, e.g. with a flight path predictor added to the tunnel-in-the-sky, which shows the aircraft position a few seconds ahead.

Past research about helicopter handling qualities in DVE demonstrated, that the pilot uses a prospective control strategy with the time to contact as main parameter, instead of using velocity and distance to obstacles [19]-[21]. Time to contact (tau) is perceived through the optical flow field, when moving through the environment. Fig. 4 shows the time to contact dependent on the visual distance and the velocity. Without visual augmentation of the flight environment, time to contact and thus time to react is reduced and therefore the velocity is influenced or safety is adversely affected in severe visibility conditions.

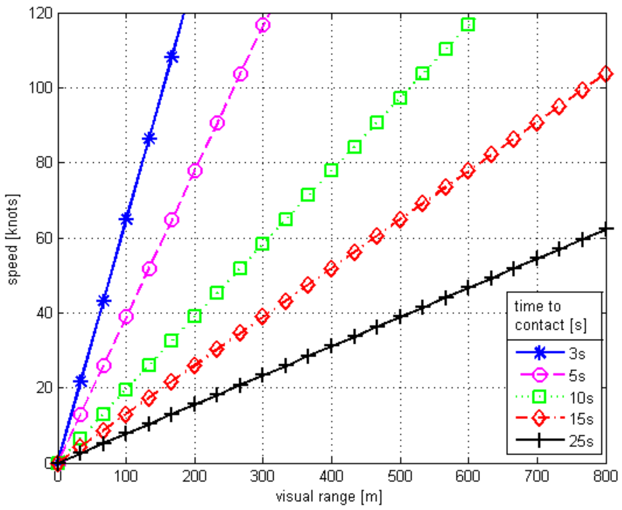

Fig. 4: Time to contact dependent on speed and visual range

Therefore, in [20], the question is, "How long do pilots look forward". For a scenario of approaching a terrain slope, it has been found, that pilots are able to maintain 6 seconds look-ahead time. That means, pilots adapt their velocity and altitude to maintain an optical flow field, which provides enough cues for about 6 seconds ahead.

Furthermore, the Visual Cue Rating (VCR) and Usable Cue Environment (UCE) concept of the ADS-33E-PRF [22] already links the control assistance with visual aids or remaining visual references to rate overall handling qualities. Dependent on the UCE, helicopter response types are demanded from basic rate command, to attitude command / attitude hold (ACAH), up to translational rate command (TRC) with position hold (PH). With high level response types, the pilot can be relieved from the task of stabilization and partially from the guidance task, thus workload can be reduced and more resources can be spent on the task of collision avoidance.

While the ADS-33E-PRF provides requirements for control assistance, sparse guidelines exist for requirements and evaluations of visual assistance systems for collision avoidance. Hence, with synthetic obstacle information, the ambition is to achieve the same guidance strategy a pilot uses in good visual environments. The key question is, how to replace the missing references in the optical flow field from the outside cues in DVE by 3D-conformal cues in the HMD. Therefore, the present difficulty of display clutter in such visualization concepts will be examined in the following chapter.

3. DISPLAY CLUTTER IN 3D-CONFORMAL HMD VISUALIZATIONS

Display clutter is a term for the undesired effect, that displayed information confuses a pilot or increases the search time to gather the required information, instead of enabling the pilot to accomplish the required task successfully and safely.

Besides display properties, like resolution, light intensity or display FoV, most quantitative investigations about display clutter with objective metrics observe the displayed content, where clutter depends on the number of objects, the density or proximity of several objects, the size of objects, the saliency and contrast to the background of objects or the structuring of entities, referred to [23]-[25]. In addition, subjective measures are examined, in which expert pilots are able to rate display clutter with developed semantic pairs for describing clutter, e.g. "redundant / orthogonal", "monochromatic / colorful", "salient / not salient", "safe / unsafe" and "dense / sparse" [24], [25].

The next subsections address some design properties, which help to structure and separate the information for improved perception through the pilot and therefore contribute to a decluttering of the display. These properties are:

- frame of reference of the visual entities
- use of color for structuring
- principle of micro- and macrotexture
- mechanisms of depth perception
- concept of information blending

3.1. Frame of Reference

3D-conformal visualizations add the possibility to place objects and items in different frames of reference, compared to non-head-tracked concepts. Besides the well accepted two dimensional information presented in the head-fixed frame of reference for aircraft and system states (ownship information), terrain and obstacles as well as flight guidance features, e.g. highway-in-the-sky or navigation route arrows, can be located geospatial-referenced. In addition, some information can be fixed to the aircraft-fixed frame of reference, like the attitude indicator. Placing this instrument always in front of the aircraft avoids mental rotations, while the pilot is not looking in the longitudinal direction of the aircraft. The cost of mental rotations with respect of the frame of reference is discussed in [23]. Furthermore, even hybrid implementations are present. The rotation of the heading tape can be fixed to the artificial horizon for example. Thus, it is aligned with the outside world and independent of both, the attitude of the helicopter and the orientation of the pilot's head. But with the limited FoV of most HMDs, the heading tape could move out of view in dynamic maneuvers. With an hybrid approach, it can shift with the pitch angle of the pilot's head, and simultaneously stays aligned with the artificial horizon. Therefore, it always remains in the FoV and additionally supports the perception of the roll angle. The pitch ladder is also a kind of hybrid element, which is attached to the aircraft, but rotates with the geospatial referenced horizon. An example of a combined 2D and 3D-conformal HMD visualization is given in Fig. 5 with a screenshot.

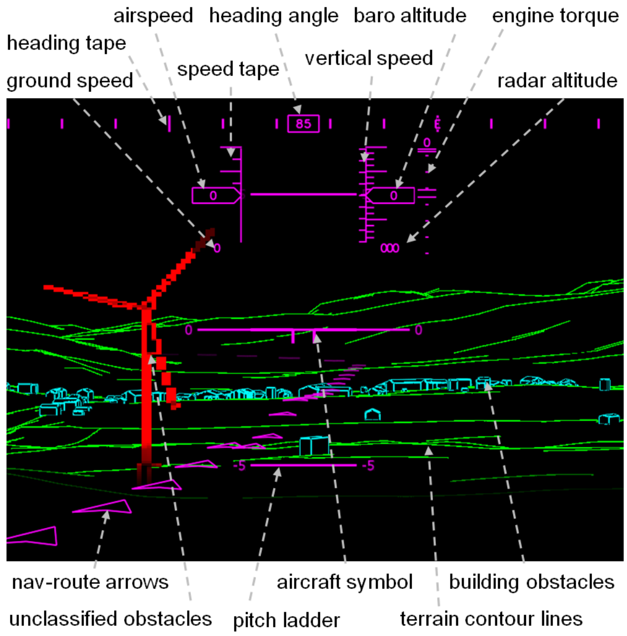

Fig. 5: Example of a color-coded 2D and 3D-conformal display combination with different frames of reference

The two dimensional head-fixed information is grouped together to maintain a "T-Pattern", as it is well known from typical primary flight displays. The arrangement is inverse and the attitude indicator is excluded, since it is positioned aircraft-fixed, as mentioned above. These rotorcraft state parameter entities are:

- heading angle and heading tape
- airspeed and speed tape
- ground speed
- vertical speed marker
- barometric altitude and altitude tape
- radar altitude
- engine torque with limits

According to the recommendation in [26], these display items should be located in the bottom part of the HMD for air-to-air applications and at the top region for air-to-ground applications to reduce the occlusion of the outside world view. Assuming that the relevant phases of DVE scenarios (approach, take-off and landing) occur close to ground and obstacles, the outside view on the bottom is more important and thus, the free space at the top is appropriate for aircraft state information. Therefore, these parameters are shifted upwards to the top region of the limited FoV.

3.2. Use of Color

Past and present HMDs in use are mostly monochrome. Thus, color was not an option and differences in visualizations could only be realized through brightness or other means to distinguish between symbols or to focus attention visually, like highlighting or blinking [27] of entities. But more and more HMDs capable of presenting colored imagery are in development and pilots desire color-coded information [11]. Care must be taken when implementing colored symbology and obstacle information within see-through displays. Most recommendations give the advice to use color very carefully and only where it is necessary and cannot be realized through other means, like different shapes of symbology elements for example. It is also recommended to use only a very limited number of colors for already structured or categorized information [26], [28].
The HMD applied for this work is capable of presenting full color, thus the developed visualization concept has been designed to use four elementary colors to aid in decluttering the large amount of information, i.e. the complementary colors of magenta / green and cyan / red. Yellow is not used, because it might be difficult to perceive this color in very bright conditions or in DVE with a similar background, like in fog, snow (whiteout) or dust (brownout). The final visualization concept uses the following colors, as shown in Fig. 5:

- magenta: all synthetic guidance and navigation symbols
- green: terrain visualization
- cyan: known objects from databases
- red: unclassified obstacles from sensor information

Such a minimal use of color is assumed to help decluttering the display. Especially the terrain visualization contributes tremendously to display clutter. All widely-used concepts to visualize the terrain with see-through capability, like contour lines or a regular grid, are distributed over the whole display and thus, lines or other geometries are drawn close to other symbology items. But with different colors (magenta / green) it is easier to distinguish between terrain lines and rotorcraft state symbology elements. In addition, a blending concept has been integrated, described in section 3.5, to ensure readability of important rotorcraft states. The other two colors are used for obstacles. Cyan, closer to green, is used for less dangerous obstacles, which are known from databases, and thus are classified. Red is used for the unknown and unclassified obstacles, which are detected by imaging or ranging sensors with a shorter warning time and therefore might be more dangerous. The Pilot should give increased attention to such obstacles.

3.3. Principle of Micro- and Macrotexture

To maintain the global optical flow, as it is necessary for tau-guidance, the surrounding environment can be rebuilt with microtextures (fine details) and macrotextures (large objects) [19], [29]. The latter can be obstacles, like poles or trees, while microtextures represent the detailed fine-grained texture of the surface of objects or small and detailed parts of a macrotexture, like branches or leaves of a tree. A more quantitative classification has been investigated in [30], with image metrics, e.g. smoothness, intensity, uniformity and density, but it still needs further validation.
Microtexture was discovered to have a strong influence on the task in low speed and hover [31]. Unfortunately, it is very problematical to use microtextures in a see-through HMD, because the fine detailed textures increase the amount of occlusion of the real world behind. In [14] the concept of emergent detail has been introduced, in which the terrain details are increased at lower altitudes with rectangular tiles added to the terrain mesh. This approach compensates for the loss of required optical flow at low altitudes, but also increases display clutter. Therefore, most recent concepts try to avoid the use of microtextures and solely rely on macrotextures.

3.4. Mechanisms of Depth Perception

The basic mechanisms of human depth perception are well explored [23], [32]. Observer-centered cues, which are more relevant at closer distances below 50 m, are:

- **Binocular disparity**: Perceiving slightly different images with each eye (stereopsis).
- **Focus**: Consisting of the eye accommodation and convergence. For the former, a muscle must form the eye lens to receive a sharp image; and for convergence, the two eyes must cross their line of sight to focus at closer points in space.

To avoid focusing problems with the outside environment, the eye accommodation is usually set to infinity distance by the optical lens system of the HMD. Therefore, it can hardly be applied purposely to assist in depth perception. Stereopsis can help to filter information and thus to reduce clutter [33], but only at relative low distances, which is only interesting for very low speeds during hover or landing tasks.
In addition to observer-oriented cues, pictorial depth cues provide monocular cues and can be used to design 3D-conformal see-through scenery visualizations. An excerpt of pictorial depth cues from [23] and [29] are the following principles:

- **Relative size**: Smaller objects appear farther away, when compared to objects, which are physically similar in size.
- **Relative density**: The texture gradient or cluster of objects, that get finer with increasing distance (compression).
- **Linear perspective**: Two parallel lines, which appear to converge, result in the assumption of depth (splay).
- **Motion parallax**: Moving objects farther away appear to have less relative motion than objects closer to the viewer.
- **Occlusion**: One object partially or completely obscures another object. The occluded object appears to be farther away.

With these depth cue principles in mind, the egomotion or locomotion of the pilot can be assisted by replacing 3D obstacles and references in an ecological approach. Thus, the expansion of the optical flow field supports the pilot in the guidance task through peripheral vision [34]. For example, a regular grid representation uses the following two principles: 1) "compression" with horizontal lines, which are more densely when farther away and 2) "splay", the angle between lines perpendicular to the horizon [23], [35]. These cues help the pilot to determine the altitude during flight. The effect is larger close to obstacles and decreases at higher altitudes, just as the gradient of the optical flow changes. Care must be taken when a regular grid texture is used as a layer mapped onto the elevation model. In case that the elevation data have a higher resolution than the applied separation for the grid lines, the lines are not straight any more. They follow the elevation in detail and therefore diminish the aforementioned depth cues. A grid texture with a separation of 100 m, rendered as a texture layer onto an elevation grid with 1 m resolution, results in bumpy lines for terrain visualization. On the other hand, using straight lines with a separation distance of 100 m for visualization loses accuracy in terrain resolution, if 1 m elevation data are available. Consequently, different visualizations are required dependent on the task, e.g. for the terrain surface at landing sites and for guidance at cruise flight, different cues and resolutions should be regarded. This has been considered in [8] with a detailed, high resolution terrain grid in the region of the landing zone.
Another cue is provided by the edge rate [23]. Regardless of using a regular grid, ridgelines or contour lines, the number of passed edges indicates the velocity of movement over the terrain surface. Contour lines additionally give valuable feedback about the terrain surface itself, especially in the mountains or in hilly areas.
Finally, in [23] and [29], it is concluded that motion parallax and occlusion are under the top three of the

most effective depth cues. Hence, section 4 focuses on the principle of occlusion using see-through displays in the application of helicopter flight in DVE.

3.5. Concept of Information Blending

The augmented reality application with a see-through HMD requires a detailed observation of what can be occluded by the displayed content without adverse effects. Two levels should be considered therefore:

1. Displayed content shall not obscure visible features in the real degraded world view.

2. Displayed content shall not mask other important display content unintended.

It is assumed, that in DVE near-field objects are still visible up to a reduced visual range. Thus, for the first level, a continuous fade-out can be applied to blend or cull all the terrain and obstacle visualization in the foreground up the visible range, like in [8]. This results in a smooth transition from the remaining outside visual cues to the synthetic cues provided by the augmentation in the HMD, see Fig. 1. Since the visible range cannot be determined automatically yet, the pilot has to set this distance manually.
The second level of occlusion originates from the dynamic content of 3D-conformal information. With only two dimensional information presented in the head-fixed coordinate frame, no overlap between separate entities will occur. But when moving the head over the 3D-conformal scenery, interferences of 3D-conformal entities in the geospatial frame of reference with two dimensional entities in the head-fixed frame of reference will be induced inevitably. To prioritize the basic rotorcraft state parameters above the scenery content, a semi-transparent background behind two dimensional entities can be rendered, thereby blending out background scenery, see Fig. 6.

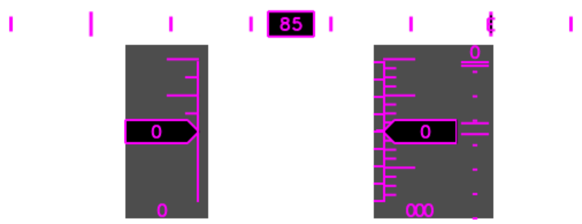

Fig. 6: Background blending elements to ensure readability of the rotorcraft state parameters

This creates a highlighting effect, which improves the readability of important information independent of head motion or rotorcraft dynamics. The level of transparency can be adapted dependent on the size and importance of the two dimensional content. The numerical values of velocity, altitude and heading, like in Fig. 6, have a black background, which results in 100 % transparency around the numerical value in the see-through display, consequently excluding any interferences with other symbology elements. Speed and altitude tapes, which give an impression of the rate of change, only have a background transparency of 70 % for example. Thus, lines of obstacle visualizations behind these entities are not cut off completely. Instead, only the brightness of the scenery is reduced in the region of more important two dimensional content.
The next section addresses the measurement of active illuminated pixels to determine the overall ratio between see-through transmission and display content, which masks the outside cues.

4. ACTIVE PIXEL RATIO MEASUREMENT FOR DETERMINING OCCLUSION IN REAL-TIME

As described above, different variants of terrain surface visualization are applicable. Moreover, a multiplicity of variants for obstacle visualization is conceivable. All variants result in different amounts of illuminated pixels for rendering, dependent on the dynamic of the head motion and thus line of sight, or the distance to ground or obstacles. To declutter the display, the ambition is to reduce the occlusion of the outside world view and therefore the amount of active drawn pixels. In [24] and [25] the ratio of active pixels in static and dynamic images of different Head-Up Display (HUD) configurations has been investigated in a post-process with a pixel analyzing application. Even with a moderate resolution of the used HMD with 800 x 600 pixels, the image processing at a frame rate of 60 Hz is a very time demanding task. Hence, for this work, an OpenGL (Open Graphics library) Shader has been implemented for the HMD render application to determine the ratio of colored pixels (every pixel, which is not rendered black) to the total amount of display pixels in real-time. It uses Atomic Counters to determine the number of magenta, green, cyan and red pixels in the rendering pipeline. An Atomic Counter is a variable type and part of OpenGL, since version 4.2. In addition, the 3D-conformal content of the display concept is implemented using the open source libraries of OpenSceneGraph (OSG). The approach of using scene graphs enables a quick implementation and adaptation of terrain and obstacle visualizations for testing different configurations in pilot-in-the-loop simulations [36].
Since all black rendered pixels are completely transparent in the see-through HMD and the symbology and scenery content is color-coded, the ratio of each color can be linked directly to the displayed content. These ratios for each color are determined by the number of active pixels of the regarded color, divided by the total amount of pixels, which is known from the display resolution. Relative

brightness is controlled by the alpha blending or the sequence of rendering according to the concept of information blending. Only pixels above a minimum threshold are counted, to distinguish them from black rendered pixels.

4.1. Active Pixel Ratio Magnitude

Fig. 7 shows the active pixel ratios, recorded over a period of 180 seconds for a flight scenario with 100 m visual range. It indicates, that the flight guidance symbology in magenta maintains a very constant level, because mainly the navigation route arrows and the attitude indicator change over time. The ratio of cyan, for buildings from databases, also stays at a quite low level with the scenario in an area of medium population density. It has to be noted, that obstacles, whether from databases or from sensor information, are only displayed at distances below 1500 m, in addition to the described near-field blending dependent on the visible range. Beyond a certain range, small and medium objects are hardly distinguishable, and usually not relevant for collision avoidance. Hence, rendering these obstacles is not necessary and would only cost additional computational resources. Obstacles from sensor information are visualized as filtered point clouds with limited resolution. Thus, an imagery or pictorial presentation has been used in this scenario, like in the example of a wind turbine in Fig. 5. The different methods for simulating sensor information require a filtering and clustering of point cloud data from ranging sensors, like in [37]. Furthermore, the approaches assume, that these point clouds can partially be classified as a group of objects and that they can be distinguished from the ground, as in [38] and [39]. The major contribution to the total active pixel ratio occurs from the terrain visualization. Higher occlusion values arise temporarily only by the pictorial imagery of obstacles, when approaching them very close, see Fig. 7 at peak values above 6 %. Even though the display seems to have a high filling degree, the mean value of occlusion is below 4 %, with peaks lower than 12 %.

Moreover, the total human FoV spans approximately 200° horizontally and 120° vertically [29], compared to the HMD used in this work with a limited FoV of 23° horizontally and 17° vertically. This results in a small display-induced occlusion factor of about 0.016 of the human FoV. Thus, only 1.6 % of the total human FoV is covered by the HMD. Despite this negligible seeming percentage of occlusion, it must be noted, that the display covers mainly the foveal view and partially the near-peripheral FoV, and therefore the most important part of the human vision system. Hence, the objective to reduce visual clutter is to minimize the occlusion in this region, without losing important cues and information quality.

4.2. Active Pixel Ratio Comparison

With this real-time measurement of the active pixel ratio, different variants of terrain and obstacle visualization can be compared objectively. Fig. 8 demonstrates a different variant for scenery presentation with a regular terrain grid and red bounding boxes for obstacles identified by sensors, in contrast to the pictorial imagery and contour lines in Fig. 5.

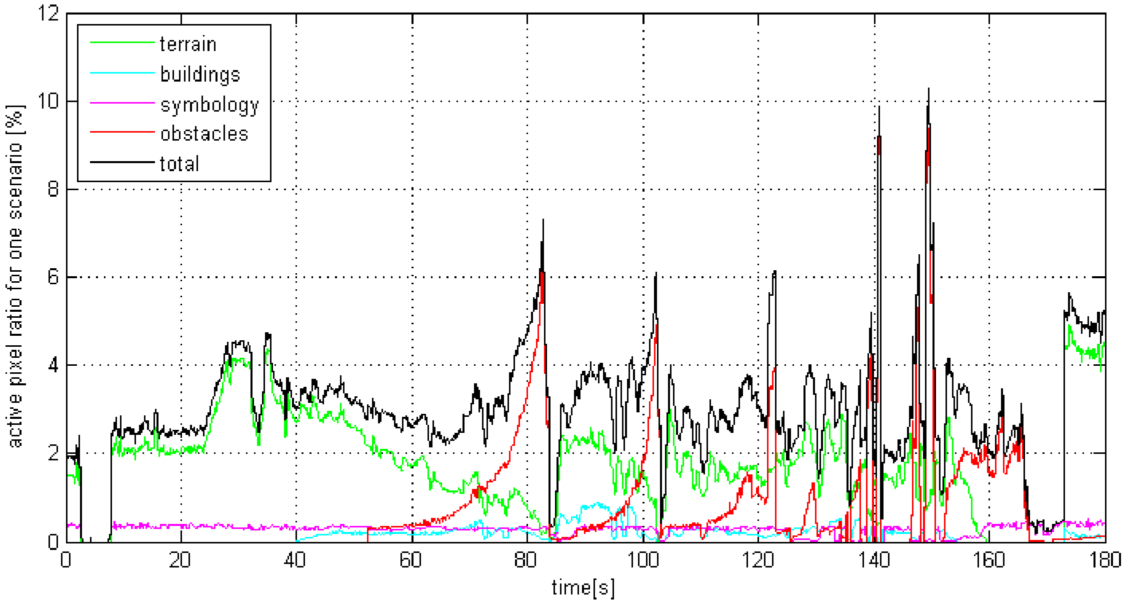

Fig. 7: Active pixel ratio for a flight with 100 m visual range over a period of 180 seconds

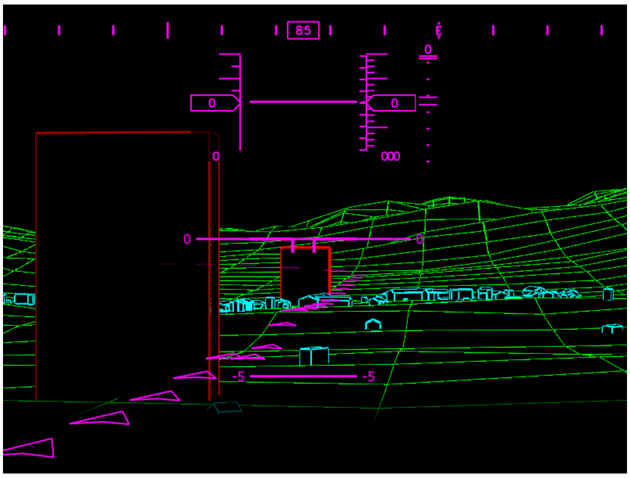

Fig. 8: A different scenery visualization variant: Terrain with regular grid and obstacles with bounding boxes

Flight dynamics and head motion data are reused from a recorded flight simulation to have equal conditions, with regard to the viewing direction and the visual content. For these examples, database objects consist of buildings with level-of-detail 2 (LoD2), which provide architectural roof geometries in addition to LoD1 bounding boxes. The buildings are rendered as wireframe, showing the complete geometry with black filled polygons to hide lines lying behind, which should be occluded to support depth perception [40]. Similar to this depiction, in Fig. 8 the red bounding boxes are filled with black polygons to hide other lines and thereby ensures, that the real obstacles in the outside world view are not obscured by terrain lines or buildings in the augmented HMD image. This is also part of the information blending concept explained earlier. Even when the near-field blending wipes out the red bounding box lines, the black polygons are still rendered to ensure see-through transmission without occlusion by other scenery content.

Fig. 9 indicates the mean active pixel ratio, subdivided into the four color-coded visual entity groups for different visual ranges, and thus their contribution to the entire display occlusion according to the scenario period shown in Fig. 7. For this terrain visualization comparison, the variant with contour lines (Fig. 5) is represented by the left bars with blue borders. The alternative version with a regular terrain grid (100 meter mesh size, Fig. 8) is depicted by the right bars with orange borders.

The variant with contour lines requires less active pixels compared to the regular grid. Of course, the active pixel ratio for the regular grid is mainly influenced by the mesh size, but for low-level flight, a grid size larger than 100 m would not be accurate enough.

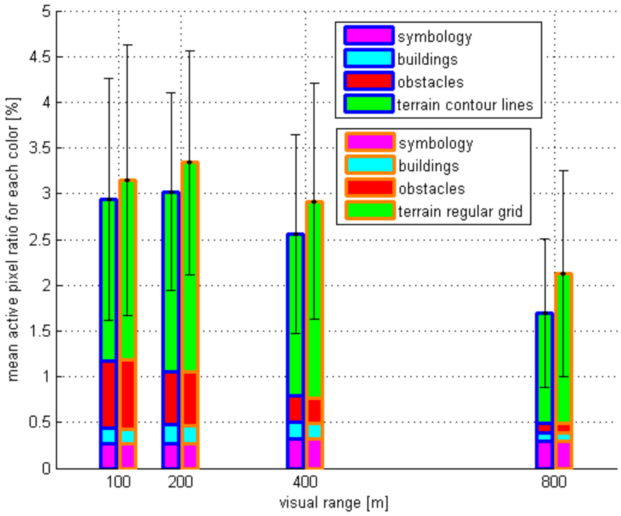

Fig. 9: Comparison of mean active pixel ratios; left bars: terrain with contour lines; right bars: terrain with regular grid

The overall percentage value decreases in both configurations with increasing visible distance, as expected due to the applied near-field blending.

4.3. Active Pixel Ratio Utilization for Reducing Display Clutter

The above described information about the active pixel ratio can be used at several different levels to reduce display clutter.

1. **Knowledge gain**: As a mean for engineers to determine the sources of occlusion and to derive improved concepts.
2. **Development of guidelines**: Definition of desired and adequate boundary values for maximum occlusion.
3. **Adaptive information control**: Using the real-time information for automatic adjustments.

From an engineering perspective, this information can be used to derive improved visualization variants with less occlusion at the one hand and a very high level of usable cues at the other hand. Considering the example of terrain visualization, the grid variant results in a higher magnitude of occlusion than contour lines, but it also provides very useful depth cues for guidance. Consequently, the two variants have been combined. The grid depiction is used for the near-field to provide the depth cues of splay and compression. At 2000 m distance from the viewer, the terrain visualization switches to contour lines, which adds cues about the far-field terrain surface, while reducing the occlusion, compared to the regular grid. In total, the combination of both variants benefits from including all important cues with less occlusion at the same time, see Fig. 10.

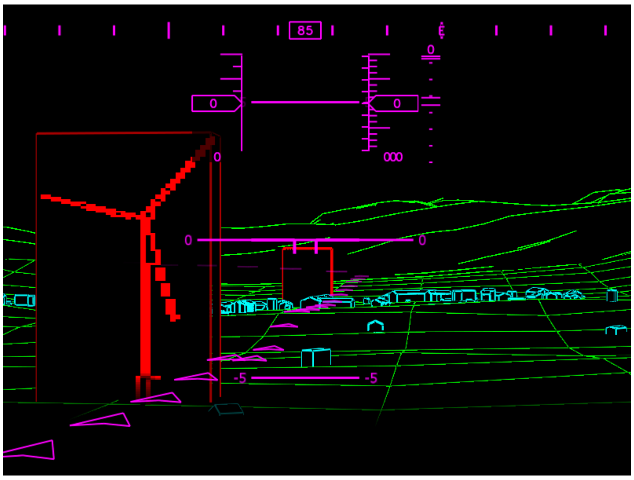

Fig. 10: Combination of terrain and obstacle visualization variants

In addition, the mean active pixel ratio of the obstacle visualization increases with lower visual ranges, as can be seen in Fig. 9. This is a result of the pictorial imagery, when the near-field blending is applied very late at distances below 200 m. Approaching obstacles, which are placed directly in the flight path, leads to peaks in the occlusion, as long as the pilot is focusing the obstacles to avoid them, as shown in Fig. 7. To prevent such peaks at short visual distances, a combination of the pictorial and the bounding box variant has been implemented. Above distances of 300 m the obstacles are displayed with the pictorial imagery concept. Approaching obstacles closer than 300 m switches to the bounding box representation with a smooth transition between both variants. With this combination, the peaks at lower visual ranges can be avoided, which also results in a lower mean active pixel ratio for obstacle visualization, see Fig. 11, without losing pictorial cues. These imagery cues may assist the pilot to identify obstacles, instead of just highlighting an area, which should be avoided. Thus overall situation awareness can be improved.

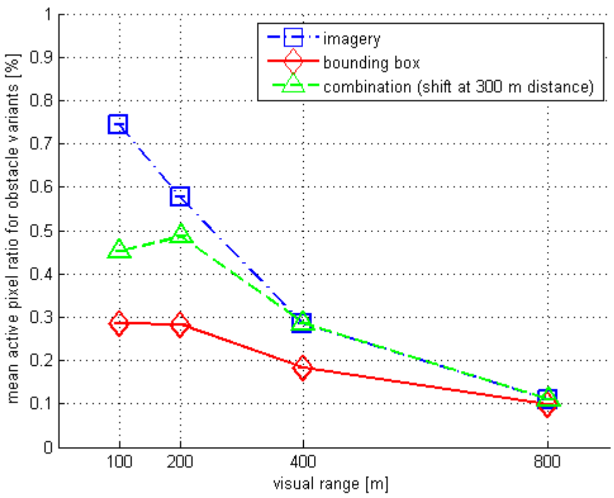

Fig. 11: Mean active pixel ratio for obstacle variants

For the derivation of guideline values in the second stage, more analysis is required to consider all possible circumstances for the regarded flight scenario in DVE. With comparison of more designs, in addition to the feedback of pilots through pilot-in-the-loop simulation studies, limits for the desired or adequate maximum allowed occlusion can be derived, dependent on the degraded outside viewing condition.
Furthermore, the active pixel ratio available in real-time has the potential to be used for an adaptive control of the occlusion in future applications. Instead of controlling the fade-out distance dependent on the visibility range, the pilot may adjust the 3D-conformal information displayed dependent on several discrete clutter mode presets. Moreover, the active pixel ratio information can be used in conjunction with adaptive automation concepts explained in [41]. With such approaches, the amount of occlusion could be controlled by real-time psycho-physiological measures, which determine the state and workload of the pilot. Finally, these adaptations must be further evaluated through simulation studies with pilots.

5. ROTORCRAFT SIMULATION ENVIRONMENT FOR ENHANCED EVALUATION

Without pilot-in-the-loop evaluations, the results above are only rateable up to a certain level. New visualization concepts can be derived and compared to well established approaches in literature, but in addition, pilot performance and the acceptance of the entire visual assistance system by the pilot must be evaluated as well. For that reason, the Rotorcraft Simulation Environment (ROSIE) [42] in Fig. 12 at the Institute of Helicopter Technology has been extended and tailored for enhanced evaluation in a safe environment to study such upcoming 3D-conformal HMD visualization concepts in severe degraded visual conditions.

Fig. 12: Rotorcraft Simulation Environment (ROSIE)

The main features of the fix-based simulator are:

- Wide FoV 6-channel projection system
- High fidelity flight dynamics model
- Original Bo105 cockpit environment

For studying visual assistance concepts, a high fidelity projection system for the outside visual cues is provided with a large FoV (horizontal 200°, vertical -50°/+30°) and a high resolution database (elevation data up to 1 m, aerial images up to 0.20 m/pixel). The flight dynamics model (GENSIM [43]) with in-flight validated data sets for a Bo105 and an EC135 has been integrated in a Matlab/Simulink development environment for simulation control and data recording. The Bo105 cockpit has been reconstructed with a flexible instrumentation panel, which consist of four interchangeable 15" touch screen panels, see Fig. 13.

Fig. 13: Cockpit view of ROSIE with four display configuration

The controls have been retained with the mechanical artificial force system and the electrical cyclic trim functionality.

5.1. Tailoring of ROSIE for HMD Experiments

For pilot-in-the-loop simulations with 3D-conformal symbology, a binocular LCD29-HMD with an InterSense IS-900 head-tracking system for a very precise (translational: 2 - 3 mm, rotational: 0.5°) and fast (180 Hz) head motion feedback has been integrated. Especially for 3D-conformal presentations, a highly accurate head-tracking with latencies below 40 ms is very important [6]. For the dynamic registration of the augmented image of the HMD against the multi-channel dome projection system, a dynamic eye-point has been implemented in the Image Generator (IG) of ROSIE [44]. Thus, each projector channel dynamically adapts the perspective and distortion to the current head position. Therefore, the distorted optical flow field is always projected correctly, compared to a simulation with a fixed design eye-point. This is important to minimize registration errors induced by the simulation environment itself, with a very limited distance to the outside screen projection. In collimated projection systems, this kind of registration errors with the outside cues are not involved, but collimated projection systems do not provide such a large vertical FoV yet.
Besides the HMD-extension of ROSIE, the cockpit instrumentation has been tailored with a reduced slim configuration, which consists of only two head-down touch screen panels, see Fig. 14.

Fig. 14: Slim cockpit configuration of ROSIE with only two displays head down

The upper display shows the primary flight information with basic rotorcraft state and system parameters and the lower can display a digital moving map for navigation. The reason for the reduced head-down instrumentation panel is the ambition to maximize the unblocked view outside and head-up, instead of blocking the view with large head-down displays. Together with the approach of augmented 3D-conformal cues in the HMD, important information is still available, even under degraded visual conditions. Of course, safety assessments must be conducted to prove such design decisions at higher technology readiness levels (TRLs).
In addition, a seat shaker has been integrated to simulate the vibration induced by the main rotor. These vibrations challenge the 3D-conformal visual registration, but also provide a high level of realism for the simulated scenarios.

5.2. DVE Simulation Scenario

For the evaluation of the described display concept, the slalom Mission Task Element (MTE) of the ADS-33E-PRF has been used as a basis for the design of a DVE scenario including obstacle avoidance. The task is to follow a given flight path with a constant height above ground, while obstacles placed in the path shall be avoided. Thus, workload is maintained relatively high, while the dynamic of the maneuver is reduced through relatively large distances between obstacles. Visibility ranges will be varied between 100 m and 800 m.

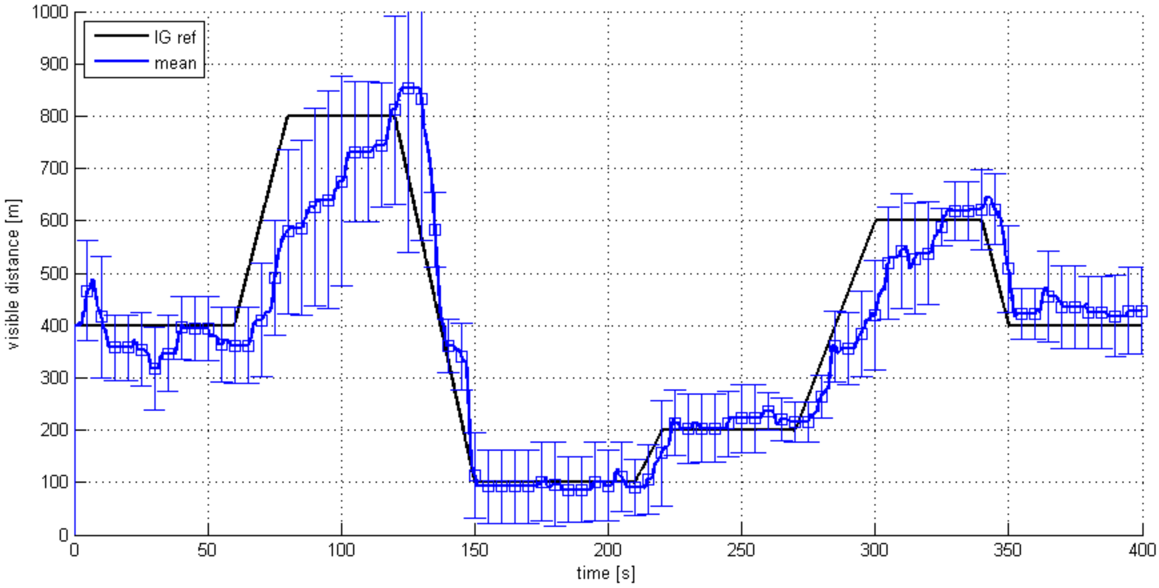

Fig. 15: Mean visible distance setting on the HMD according to the simulated Image Generator (IG) reference

With the planned experiment in late 2015, different display variants will be studied. It will show, if the display with reduced clutter, but rich of 3D-conformal information, can achieve compliance with the control strategy of pilots and hence, the tau-theory.
In addition, a small preliminary study with students has been conducted, to show, if they are capable of adapting the visible distance for the near-field blending. Therefore, the task of flying the helicopter has been removed and a recorded flight has been simulated. The students observed the environment through the HMD and adapted the setting of the near-field blending distance to the visual range provided by the outside visual cues. The degraded visual conditions have been generated by the Image Generator (IG) of ROSIE with fog at varying distances, see black signal (IG ref) in Fig. 15.
Furthermore, it shows the mean visible distance setting of the five participating students together with the standard deviation at several points in time. Regarding the overall tracking, the students performed very well without additional tasks and with a mean standard deviation of 87 m. At lower visual ranges they achieved better results than at higher distances. The case of setting the visible range to larger distances required a longer period of time to realize, that the visible conditions have improved, compared to the case of reducing the visible distance, see larger deviations from the reference with increased variances (60 s - 120 s, 270 s - 330 s). This is not as critical as in the latter case, in which the distance to the fog is lower than the setting for the augmented HMD visualization. In this case, important information is neither visualized in the HMD, nor is it visible through the outside cues. Here, the students responded faster and with high precision (120 s - 150 s, 340 s - 350 s).
In the final study, it will be investigated, if pilots are able to achieve comparable results, even during manual flight with moderate to high workload conditions.

6. CONCLUSION

This work analyzed the principles behind visual perception of pilots in low-level flight with degraded visual conditions. The control strategies of pilots and mechanisms of perception have been examined to provide means for reducing visual clutter. In particular, the principles of using different frames of reference and colors can guide the design to be well structured. Furthermore, with the fundamentals of depth perception, indications for beneficial 3D-conformal content can be established. Finally, the concept of information blending is a powerful design property for decluttering information in see-through HMDs.
The amount of occlusion, with a high impact on the see-through capability, has been measured. Although HMD solutions require further analysis of the division of attention between the synthetic augmented image and the degraded real outside view, reducing the active pixel ratio, and thus occlusion, contributes to the mitigation of this effect.
Besides the usability as a tool for improved engineering solutions and comparison of different designs, the mean active pixel ratio has the potential to be further applied for guideline values or adaptive control in real-time.
In spite of all these optimization efforts, pilot-in-the-loop simulations are required for the evaluation of this human-machine interface. Therefore, the Rotorcraft Simulation Environment has been extended and tailored to satisfy this need. Moreover, validation scenarios have been developed and

implemented for a planned simulation experiment in late 2015.

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