3D PERSPECTIVE VIEWS ON IMMERSIVE HEAD-WORN DISPLAYS – CAN EXOCENTRIC VIEWS INCREASE PILOT SITUATIONAL AWARENESS?

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Abstract

The airframe restricts the helicopter pilot's view of surrounding obstacles, especially below and behind the rotorcraft. State-of-the-art solutions fuse data from aircraft-mounted sensors (e.g. radar, lidar) with database information. The resulting picture of the environment is usually presented on panel-mounted cockpit screens or on head-worn, see-through displays. This paper explores a novel display approach called "Virtual Cockpit", which overcomes limitations of today's solutions. In particular, we evaluated how 3D exo- and ego-centric perspective views – shown on an immersive head-worn display – improve pilot situational awareness and performance. A simulator study with eight participants revealed the great potential of exocentric views combined with visual conformal symbology. Spatial awareness and position holding during a hover maneuver next to a wind turbine were improved compared to a conventional cockpit view. Nevertheless, the study showed that the pilots' ability to judge and control helicopter attitude requires further investigation. The results of this paper are applied to current research on all-weather helicopter operations. Moreover, the findings are relevant for the development of future remote piloting solutions or external vision systems for aircraft with highly restricted cockpit window areas, for instance armored military aircraft or future hypersonic airplanes.

1 Introduction & Related Work

A pilot's out-the-window view is heavily restricted by non-transparent parts of the airframe. Helicopter pilots are hardly able to see the surroundings and threats below, above, and behind them. Moreover, the amount of usable outside visual cues is often drastically decreased, for instance due to fog, heavy precipitation or darkness. As the outside vision constitutes an important information source for pilots, it is highly desirable to develop solutions that enable operations when the natural vision does not provide enough information to safely fly the helicopter.

State-of-the-art solutions gather information about the environment by fusing data from various aircraft-mounted sensors (e.g. radar, lidar) with information from databases [9]. The resulting picture of the environment is superior to the unaided human vision under many degraded visual conditions like darkness or fog. To convey the gathered data to the pilot, two types of displays are used in today's cockpits: conventional panel-mounted displays (PMD) and see-through head-up or helmet-mounted displays (HUD, HMD) [8, 11]. The former offer a full color representation and give the display designer great freedom in the way flight guidance information is presented. However, such synthetic or enhanced vision displays can only show a down-scaled projection of the 3D environment on rather small flat panel screens. Further, they tie the pilot's head down to the instrument panel. Head-up and head-worn displays, on the other hand, allow the pilots to focus their eyes out of the cockpit as they superimpose the real-world view with symbology providing additional cues [10]. Head-worn displays have been used in the military domain for many years. Recent technology advancements give reason to predict wide usage of such devices also on civil flight decks [1]. Nevertheless, these augmented reality solutions also suffer from a number of weaknesses, for instance limited field of view, brightness issues, or color perception problems [7].

Our solution combines advantages of both worlds – 3D perspective head-down and visual-conformal head-up/helmet-mounted displays – by using an immersive/non-see-through head-worn display (iHWD) [3]. The chosen display type enables us to present a full-color, 3D perspective view without scaling the picture down to a flat panel screen. Via head-tracking system, the viewing direction can be coupled to the pilot's head movements implying that the pilots can naturally look around the displayed scene just by turning their heads to the point of interest. Further, exocentric perspectives can be realized. This means that the pilot's viewpoint is moved out of the cockpit, for instance to a location behind and above the own aircraft. Thus, they can virtually look below, behind, and above their own aircraft – areas they cannot see from a conventional cockpit.

Three-dimensional ego- and exocentric display perspectives have been thoroughly discussed in research on synthetic vision navigation and primary flight displays. Costs and benefits of different viewpoints and perspectives are well-documented [2, 13]. However, previous research on exocentric views deals with head-down display representations, whereas the proposed approach covers head-tracked, head-worn displays. Moreover, this work places the focus on helicopter-specific tasks like hover and land in close proximity to obstacles.

The main question of this research is: how can we support helicopter pilots maneuvering with degraded vision in confined areas? In this paper we will investigate if exocentric views and egocentric views with transparent aircraft hull can increase situational awareness. A simulator study will evaluate the following: 1) Do the novel 3D perspective views on iHWDs improve the pilots' perception of the environment, especially their distance and position estimation relative to obstacles? 2) Is it still possible to control the helicopter by using these perspective views?

The paper is structured as follows: Section 2 explains the concept of our *Virtual Cockpit* and introduces the four display variants tested in our simulator study. The following sections 3 and 4 present the method and the results of the experiment. Section 5 concludes the paper with a discussion and a look on future work.

2 Display Concept – Virtual Cockpit

Our *Virtual Cockpit* concept comprises two major parts: a sensor and database module that provides all required information about the environment, and a display module showing a 3D perspective view on an iHWD. This paper focuses on the latter. The full concept and its expected advantages are described in [3, 4].

3D perspective views This contribution introduces four 3D perspective views to be shown on an iHWD. Two layouts, called *Cockpit-Base* and *Cockpit-Trans*, use an egocentric viewpoint, while the other two, *Exocentric-Base* and *Exocentric-Trans*, show the situation from an exocentric viewpoint.

Cockpit-Base replicates a conventional cockpit and serves as a baseline for the experiment. As illustrated in Figure 1 (right), *Cockpit-Trans* virtually creates an unblocked view of the environment by making the helicopter fuselage transparent. Note that important parts of the structure are retained as a visual reference. Figure 2 presents *Exocentric-Base* and *Exocentric-Trans*, which are mostly similar. The only difference is the helicopter being transparent in the latter layout. This is to obscure objects ahead of the helicopter as little as possible. The main feature of these exocentric variants is that the pilots are virtually taken out of the cockpit to a viewpoint behind and above the helicopter. This provides the pilots with a view of the whole space around their helicopter, without even turning their heads. Accordingly, they are expected to improve spatial awareness. In the tested version, the exocentric camera is not coupled to pitch and roll rotations of the helicopter. This implies that the camera remains at a stable position behind and above the aircraft reference point. It also means that the horizon stays horizontal regardless of aircraft bank. Similarly, the horizon does not move vertically in the pilots' field of view (FOV) when they alter the pitch angle.

A very important plus of the head-worn display is that the pilot can naturally look around in the 3D synthetic environment by turning the head. This is a very important advantage over panel mounted displays.

Finally, each 3D perspective view is equipped with a standard primary flight display (PFD). It is located at its common place in the cockpit views. The exocentric layouts integrate it as a virtual, semi-transparent instrument on the lower left of the helicopter.

Visual conformal Symbology *Cockpit-Base* serves as an experiment baseline: a conventional cockpit with no additional assistance features. The other three novel perspective view displays are enhanced with visual conformal symbology. This is a well-established way to integrate additional information as a scene-linked overlay into the pilot's view. Its advantages have been shown for see-through head-/helmet-mounted displays (HMDs) and head-up displays (HUDs) [10]. Here, this technique is applied to enhance the judgment of helicopter position and distance relative to the surroundings. As explained by Wickens [14], perspective views come with the cost of impaired object location perception called "line of sight ambiguity". This problem exists in all perspective views including the egocentric cockpit view. In exocentric views, it is even greater because the location of both the ownship and the obstacle can not be determined precisely. As shown in Fig. 2, a green line pointing vertically from the helicopter down to the ground is integrated to overcome this problem and to enable precise position judgments. This dropline should be used to steer the helicopter to the desired hover position, which is marked by a green dot on the ground. To improve the estimation of obstacle distances, the helicopter outlines and a safety margin of half a rotor diameter are visualized by the blue lines depicted in Fig. 1 and 2. This symbology can be projected onto the ground or onto the target height. In this paper, the latter option was chosen. In addition to the described helicopter-fixed symbology, the desired hover point is highlighted by a green ball with a dropline, which disappears when the helicopter comes closer than 7 m. Finally, the ocean surface of the synthetic vision is represented by a special grid symbology. Further information about this representation, which also includes wind strength and direction, can be found in [5].

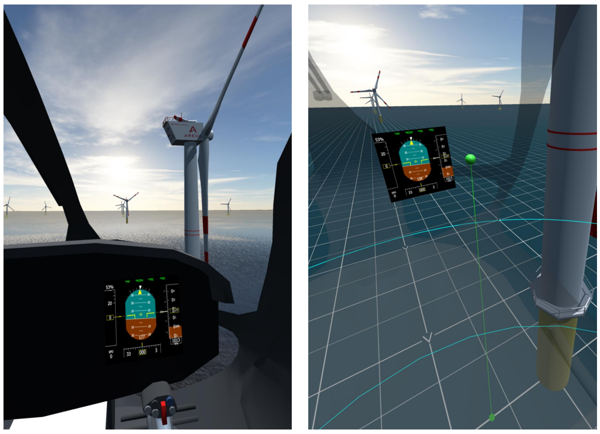

Fig. 1 – *Cockpit-Base* (left) and *Cockpit-Trans* (right) while approaching the desired hover position. In the latter, the target position and the size of helicopter and safety margin are highlighted by a visual conformal overlay.

3 Simulator Study – Method

The main objective of our simulator study was to gain insights if different 3D perspective views presented on immersive/non-see-through head-worn displays (iHWDs) can support helicopter pilots maneuvering close to obstacles. The experiment compared how precise pilots could find and hold a hover position close to a wind turbine tower. Further, we were interested in control behavior and

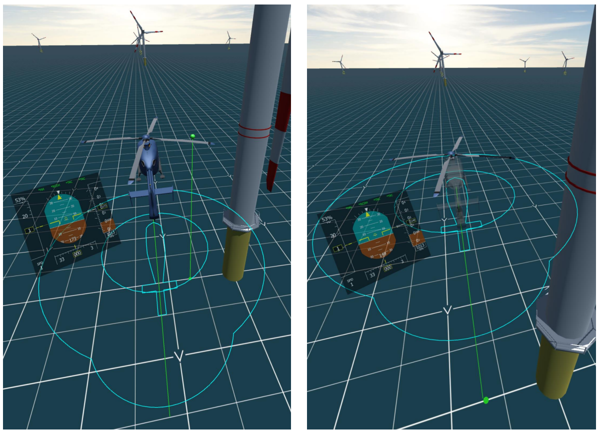

Fig. 2 – *Exocentric-Base* during the approach (left) and *Exocentric-Trans* during the hover (right). Visual conformal symbology shows the target position, the ownship position over ground, and the size of helicopter and safety margin.

impact on workload and situational awareness.

3.1 Apparatus / Simulation Environment

Head-worn display The 3D perspective views presented in Sec. 2 were displayed on the Oculus Rift CV1 virtual reality glasses. As can be seen in Table 1, this consumer electronics device provides a stereo image with rather large FOV via two high resolution OLED displays (one per eye). Head position and orientation tracking is realized through an inertial measurement unit (IMU) and an external infrared sensor detecting several infrared LEDs embedded in the goggles.

Table 1 – Oculus Rift CV1 specs

Display Type	OLED
Resolution (per eye)	1080 x 1200
Refresh Rate	90 Hz
Field of View[a]	≈110°
Head Tracking	optical, inertial
Data Interfaces	USB 3.0, HDMI

[a] Depends on individual lens to eye distance.

Flight simulator The experiment took place in our fixed base Generic Experimental Cockpit (GECO), where professional, active force feedback helicopter flight controls were installed. The outside vision and the cockpit displays were deactivated because the pilots were fully immersed in the virtual environment created by the non-see-through iHWD. Two workstation PCs were used for flight simulation, display generation and data recording. The virtual reality (VR) glasses were connected to an NVIDIA GeForce GTX 1070 video card. The data transfer between the software modules was realized via shared memory and Ethernet.

Fig. 3 – Simulator setup with virtual reality goggles and active force feedback helicopter controls.

Flight control model A custom-made flight model of the DLR EC135 research helicopter with automatic flight control system (AFCS) was used for the experiment. The AFCS was developed by DLR [6] and allowed us to apply various command types and hold modes to the four flight control axes. We enabled the *rate command, direction hold* mode for the pedals, which means that the helicopter holds its current direction when the pedals are in neutral position. Moving the pedals commands a yaw rate. The lateral and longitudinal cylic axes were in *attitude command, attitude hold* mode allowing the pilots to set an attitude, which is held in neutral stick position. Via the collective the pilots could directly set the vertical speed. The aircraft remained in level flight when the collective stayed in its middle position (*vertical velocity command*, *height hold*). In conclusion, this means that the control axes were mostly uncoupled. Without disturbances the helicopter would remain in straight and level flight if the flight controls were not touched.

In this experiment we simulated steady headwind with gusts varying in strength and direction. The impact of the wind was intentionally not compensated by the flight control system. Pilots had to continuously alter their control inputs to compensate for the constantly changing drift of the helicopter.

We chose the uncoupled, highly-augmented flight control system to place to the focus on the display evaluation, not on the flying task. Nevertheless, we forced the pilots to constantly monitor their motion relative to obstacles and adapt their aircraft attitude accordingly by simulating fast changing wind conditions.

3.2 Participants

Eight male subjects with an average age of 39 (range from 32 to 49) participated in the study. Four hold a helicopter license (1 ATPL, 2 CPL, 1 PPL). The remaining participants had no helicopter license but were experienced in flying our helicopter simulator, had comprehensive practice with the used AFCS command model, and hold a fixed-wing license. The mean flight hours was 941 h (min: 200 h, max: 3100 h). Three pilots had a mean experience of 30 h with head-mounted displays in flight, while six subjects used VR goggles before.

3.3 Experimental Design & Procedure

The experiment compared four 3D perspective views (*Cockpit-Base*, *Cockpit-Trans*, *Exocentric-Base*, *Exocentric-Trans*) using a between-subject design. The study comprised two separate tasks: a hover task close to an offshore wind turbine and a landing task on an offshore platform. In total, each participant conducted 16 flights: 8 per task type and 4 per display condition respectively. All four flights with one display type were executed consecutively. In two of these runs the pilots landed on the platform, in the other two they hovered next to the wind turbine. The sequence of these display blocks and the task order was counterbalanced.

The experiment started with a briefing, followed by a comprehensive training for the pilots to practice the flight tasks and learn the specifics of the four display variants. After a first break, the actual testing phase was conducted in two blocks of eight flights (approx. 40 min) separated by a 15 min break. Subjective feedback was gathered with the 3D SART [12] after each condition and a tailor-made questionnaire during the final debriefing. The whole experiment lasted around three hours.

3.4 Task

Each run was started in-flight, 250 ft above and 0.25 NM from the target position. Pilots took over controls at 40 knots airspeed with 15 knots headwind. The helicopter was already aligned for a straight approach against the wind. In the hover scenario, the pilots' task was to: 1) approach the target hover position, 2) acknowledge "on position" by pressing a button on the cyclic stick, and 3) hold the position as precisely as possible for 2 min. As depicted by the green dot in Fig. 2, the desired hover point was positioned directly left of the wind turbine tower. The clear distance between rotor tips and wind turbine was defined as half a rotor diameter, which is equal to the distance displayed by the visual conformal safety margin. This task was derived from a real maneuver performed by offshore rescue helicopters [4]. The target altitude of 148 ft above the water was marked by red circles on the wind turbine tower. Figure 1 and 2 (left) show the approach phase of the task from different perspectives. Figure 2 (right) depicts the helicopter in the desired hover position. As described in Sec. 2, each display variant included a standard PFD as the only flight instrument available.

The landing task comprised a straight approach and ended hovering sideways to a landing position with obstacles in front and in the back of the helicopter. This paper places its focus on the results from the hover task only.

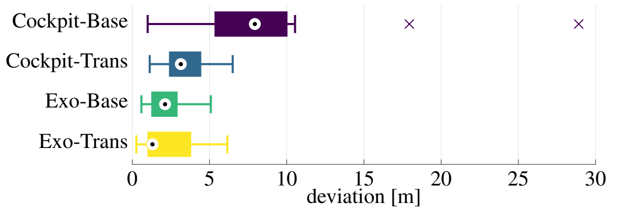

Fig. 4 – Position deviation from desired hover point at the start of the hover maneuver. Boxplots show median (circle), 25th and 75th percentiles (bar), and outliers (x) with whisker length 1.5 IQR.

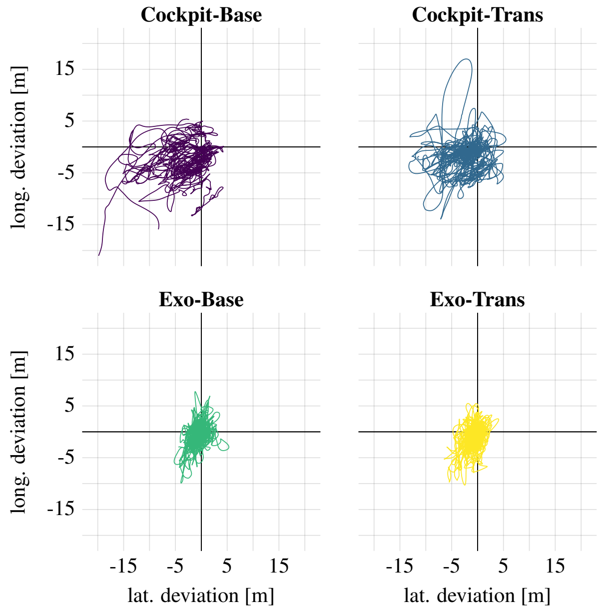

Fig. 5 – Top down view of the flight paths during the 2 min hover phase.

4 Simulator Study – Results

This section provides a summary of objective flight performance measures, which was generated by processing the recorded flight data with the data analysis software MATLAB. Additionally, subjective feedback provided via questionnaires and from oral discussions is summed up below.

4.1 Flight Performance

The first part of the pilots' hover task was to find the desired hover position and acknowledge "on position" by pressing a button on the cyclic stick. This was to measure how precise the pilots could estimate their spatial location with the tested 3D perspective view. Figure 4 shows the delta between the actual target point and the position chosen by the pilots. The boxplots show clear differences between the conventional cockpit *Cockpit-Base* and the other display conditions. Also, the exocentric variants appear to be slightly better than the transparent cockpit. Further analysis shows that especially the lateral deviation was very low with the three non-baseline display conditions.

Furthermore, we were interested in how well pilots could hold the desired position during the 2 min hover phase. The differences between the display conditions are illustrated in Fig. 5, which shows top down views of all flight paths. The area covered while using the exocentric perspectives appears to be lower than with the cockpit views. Moreover, the flight paths of the former are nearly centered around the target spot while the pilots tend to have the target on 1 or 2 o'clock position when in cockpit view.

For further evaluation, we classified the position deviations experienced over the 2 min hover phase: differences smaller than 2.5 m are categorized as "desired", deviations up to 5 m correspond to "adequate". Figure 6 depicts the overall duration within these zones for the tested display conditions. The pie charts indicate that pilots sitting in the conventional VR cockpit stayed outside the "adequate" 5 m radius more than half of the time. In only 11 % of the time, they were within the "desired" range. This performance is improved with *Cockpit-Trans* but the participants still hovered one-third of the time "out of bound". With both exocentric perspective views, the helicopter was within the "desired" limits around 50 % of the total hover time. "Out of bound" times were significantly lower with slight advantages for the *Exocentric-Base* display.

To evaluate the pilots' ability to judge and control helicopter attitude in the tested perspective views, the distributions of recorded pitch angles are plotted in Fig. 7. The boxplots are based on eight single pitch measurements per second, that is 960 values per run. As expected, the medians of all display conditions are approximately equal.

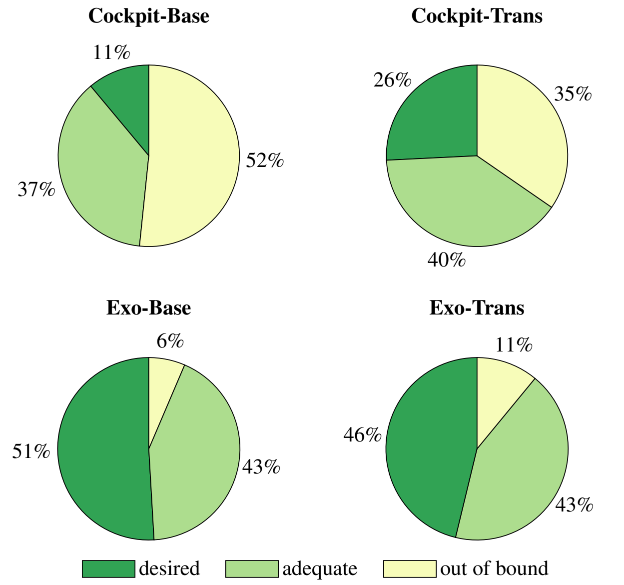

Fig. 6 – Position deviation during the 2 min hover phase. Pie charts show the overall duration within three classes based on deviation from the desired position: "desired" (< 2.5 m), "adequate" (< 5 m), and "out of bound".

However, the width of the distribution is smaller for *Cockpit-Base* than for *Exocentric-Trans* while the other two variants range in between. This means that the participants commanded higher maximum and lower minimum pitch angles with the three novel display types. The fact that the width of the boxes representing the middle 50 % of the values varies less than 1° between the display conditions, indicates that the overall difference is relatively small. Further computations reveal that fewer than 1 % of the angles deviate more than 10° from the median in the non-conventional views.

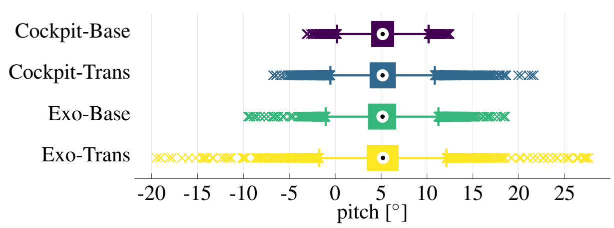

Fig. 7 – Distribution of recorded pitch angles during the hover maneuver. Boxplots show median (circle), 25th and 75th percentiles (bar), and outliers (x) with whisker length 1.5 IQR.

4.2 Subjective Feedback

The 3D SART [12] questionnaire revealed small differences between the four display conditions. The mean total scores were 83.75 for *Cockpit-Base*, 88.75 for *Cockpit-Trans*, 96.88 for *Exocentric-Base*, and 103.13 for *Exocentric-Trans*.

The debriefing questionnaire showed a clear advantage for both exocentric perspective views regarding the judgment of the distance to obstacles. Pilots stated that they "could easily judge the distance to obstacles in the back of their helicopter" from an exocentric viewpoint, whereas this appears to be nearly impossible from inside the cockpit regardless of helicopter fuselage transparency. The cockpit variants were rated better for estimating the distance to obstacles in front and on the side but still not as good as their exocentric counterparts. Further, a slight advantage could be seen for the transparent compared to the conventional cockpit view. Height estimation as well as lateral and longitudinal movement control seemed to be adequate for all display conditions.

A comparison of the cockpit with the exocentric viewpoint in Fig. 8 shows the same tendencies. Exocentric was reported to improve spatial orientation and collision avoidance creating a feeling of safety. However, all participants agreed that "helicopter attitude control is easier in the cockpit view". The exocentric views seemed not to increase workload but pilots did not agree if they have the potential to even reduce workload.

Figure 9 illustrates the rating of the visual conformal symbology, which was available in all display conditions but the conventional cockpit view *Cockpit-Base*. In general, the visual conformal overlay was rated very positive for the exocentric perspective views. However, minor flaws of the symbology in the cockpit view are visible. Both the safety margin circle and the green target balls were clearly rated to be useful. The projection of the target point on ground together with the vertical green line, appeared to be of major help in the exocentric view conditions. For *Cockpit-Trans* the individual ratings are wide-spread and in summary lower. Minor flaws of the visual con-

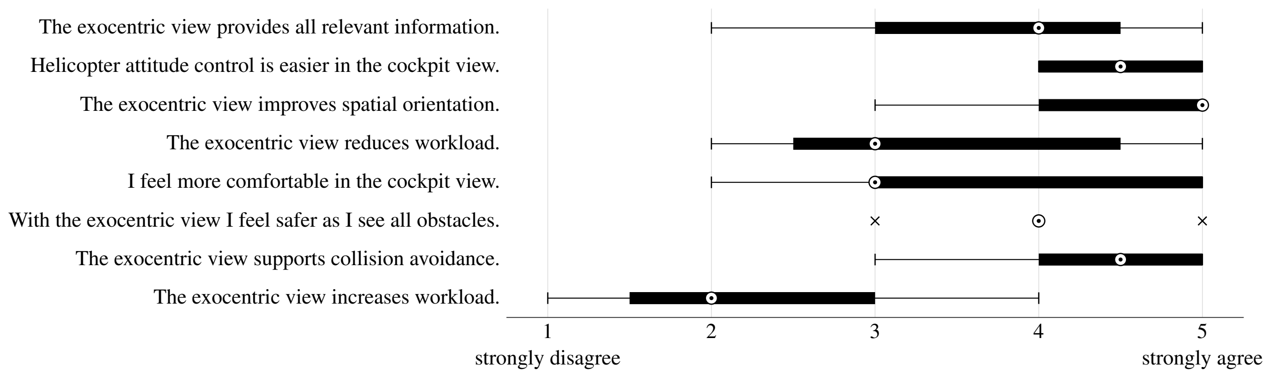

Fig. 8 – Comparison of cockpit and exocentric view. Boxplots show median (circle), 25th and 75th percentiles (bar), and outliers (x) with whisker length 1.5 IQR.

formal symbology in the cockpit view are also visible from the last statement regarding unnecessary complexity and confusion. For instance, the vertical green dropline was hardly usable in this display condition since the pilots had to tilt their heads far down to see the line and the target dot under the aircraft.

5 Discussion & Conclusion

The experiment showed that the tested exocentric perspective views with visual conformal overlay have clear advantages over the conventional cockpit view presented on an immersive/non-see-through head-worn display (iHWD). In the simulated hover scenario, pilots could find and hold the desired hover point more precisely. Additionally, both cockpit views required frequent line of sight changes between the straight aircraft direction and the obstacle on the right. With the exocentric views on the other hand, the participants could see the helicopter, the obstacle and the virtual PFD at the same time without turning their heads. Thus, they could keep their heads in a less strenuous pose while the head movements increased workload in the cockpit views. This result is in line with Wickens [14], who states that an “exocentric 3-D display is often considered superior for many situation awareness tasks”, because the small FOV hides critically important features and creates a “keyhole effect”. As can be seen from Fig. 5, subjects tried to mitigate this problem by hovering left behind the target position in order to have the obstacle at 1 or 2 o’clock instead of the desired 3 o’clock position. Similarly, heading changes out of the wind, towards the wind turbine could be observed now and then. Future research should investigate if an increased peripheral FOV in the egocentric perspective can decrease this drawback.

The transparent cockpit view with the overlying symbology also improved the pilots’ ability to find the target hover point. However, during the 2 min hover phase the subjects could not hold this position as precise as with both exocentric display conditions. Even though the visual conformal symbology shows the desired obstacle distance, participants could not fully translate this auxiliary information to better performance. Similar to *Cockpit-Base*, one important reason may be the continual line of sight changes required to gather all information about the situation. Additionally, judging the lateral position from a viewpoint behind the aircraft is obviously easier than from an egocentric view in line-of-sight direction.

On the other hand, the study showed that participants commanded higher maximum and lower minimum pitch angles with all three novel display types. This can be partially explained by missing visual cues, which the pilots usually use in a conventional cockpit. In case of *Cockpit-Trans* many references like the instrument panel were missing or less apparent due to transparency. The exocentric views are highly different in terms of attitude perception. When pilots sit inside the cockpit, the airframe remains stable but the hori-

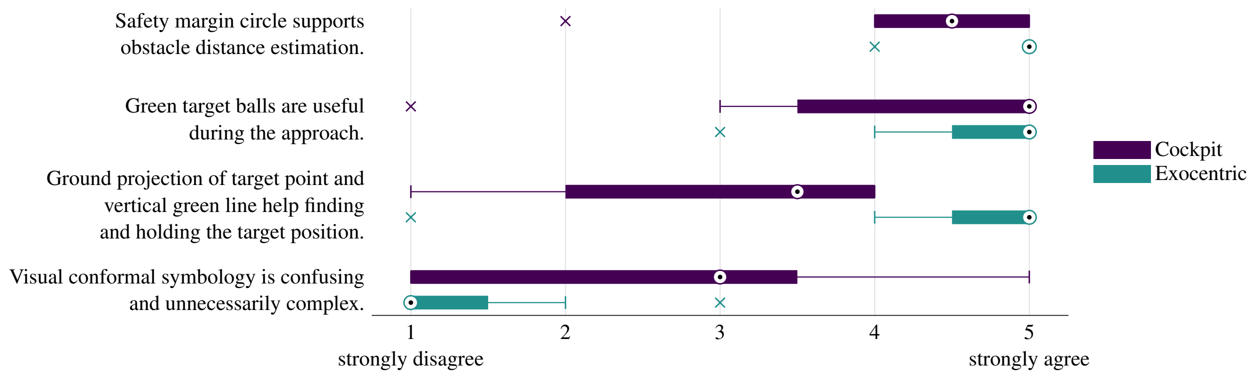

Fig. 9 – Rating of the visual conformal symbology introduced in Fig. 1 and 2. Boxplots show median (circle), 25th and 75th percentiles (bar), and outliers (x) with whisker length 1.5 IQR.

zon moves within their FOV. This is the most striking and most important visual cue for pilots judging aircraft attitude in good visibility. In the tested exocentric views, the camera remained in a stable pose relative to the aircraft reference point. This implies that the horizon was always horizontal and did not move vertically in the pilots' view when they altered the pitch or roll angle. Thus, the helicopter attitude could only be derived from the rotation of the helicopter model or the artificial horizon in the PFD. Of course, both options are less striking and noticeable than the movement of the horizon which covers the whole FOV in the egocentric view. Reading the attitude from the PFD requires the pilots to focus on the instrument while the movement of the horizon is unconsciously perceived even by peripheral vision. As a solution, we are currently investigating various options to couple the exocentric camera to the helicopter attitude. A secondary explanation for larger pitch amplitudes can be that pilots tried to control the helicopter position more precisely because they could see even small deviations with these advanced displays. The strong gusts in our experiment required high pitch angles to quickly compensate for induced drift speeds.

As a side note, the position deviations during hover were relatively large due to the challenging wind conditions. This was intentionally chosen to better see the differences in pilot behavior and performance within this part task experiment. In today's practice, this maneuver is flown with assistance from the hoist operator in the back of the helicopter [4].

These objective flight data results agree with the findings from the debriefing questionnaire and pilots' comments. Improved spatial and obstacle awareness of the exocentric views as well as easier attitude control in the cockpit view were confirmed by subjective pilot feedback.

In conclusion, the experiment revealed the great potential of 3D exocentric perspectives displayed on immersive head-worn displays. Compared to an unaided, conventional cockpit view on the iHWD, the pilots' spatial awareness was significantly improved during the hover maneuver near a wind turbine tower. Nevertheless, the study showed that the pilots' ability to judge and control helicopter attitude should be further investigated. The transparent cockpit perspective appears to have certain advantages over the nontransparent aircraft hull, too. However, the overlay symbology should be optimized for this view.

Future work should also analyze attention fixation issues regarding the visual conformal overlay. Moreover, a comparison between an immersive exocentric view display and a see-through HMD in a conventional cockpit as well as the combination of two complementing perspectives in one view are planned for future studies.

The results of this paper are applied to our current research on all-weather helicopter operations. Nevertheless, the findings are also relevant for the development of future remote piloting solutions or external vision systems for aircraft with highly restricted cockpit window areas, for instance armored military aircraft or future hypersonic airplanes.

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