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Virtual Cockpit: an immersive head-worn display as human–machine interface for helicopter operations

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Abstract. Increasing the pilot's situational awareness is a major goal for the design of next-generation aircraft cockpits. A fundamental problem is posed by the pilot's out-the-window view, which is often degraded due to adverse weather, darkness, or the aircraft structure itself. A common approach to this problem is to generate an enhanced model of the surroundings via aircraft-mounted sensors and databases containing terrain and obstacle information. In the helicopter domain, the resulting picture of the environment is then presented to the pilot either via a panel-mounted display or via a see-through head-worn display. We investigate a third method for information display. The concept—called Virtual Cockpit—applies a nonsee-through head-worn display. With such a virtual reality display, advantages of established synthetic and enhanced vision systems can be combined while existing limitations can be overcome. In addition to a theoretical discussion of advantages and drawbacks, two practical implementation examples of this concept are shown for helicopter offshore operations. Two human factors studies were conducted in a simulation environment based on the game engine Unity. They prove the general potential of the Virtual Cockpit to become a candidate for a future cockpit in the long term.
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Keywords: virtual reality; head-worn display; helmet-mounted display; degraded visual environment; enhanced vision.

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1 Introduction and Related Work

Even with today's highly advanced helicopters, degraded visual environment (DVE) poses a major challenge for pilots. DVE includes adverse environmental conditions such as darkness at nighttime or weather phenomena such as fog, clouds, or heavy precipitation. Further, the term DVE covers white-/brown-out conditions and also restricted external vision caused by the helicopter's own structure. The fact that rotorcraft often operate close to terrain and manmade objects makes DVE even more dangerous.

As helicopters perform many important tasks in the military and civil sector, it is crucial to find solutions that allow 24/7 operations regardless of visual conditions. In the future, this could—for instance—enable life-saving helicopter emergency medical services (HEMS) even if the pilot's natural out-the-window view is degraded.

Aircraft-mounted sensors and databases are a common way to enable flying in DVE. Data from various types of sensors (e.g., lidar, radar, and infrared) and database information can be fused to generate an image or model of the surroundings, which in many DVE conditions is superior to what the pilots see with the naked eye. For example, Airbus' HELLAS-A lidar sensor is designed to detect 5-mm thin wires at over 700 m distance.[1] In addition, 360-deg near-field sensors provide vision of areas behind and on the side of the helicopter, which are hardly visible for the pilot. Airbus' rotorstrike alerting system[2] and AugustaWestland's obstacle proximity lidar[3] are examples of such systems that help to avoid object strikes.

After gathering and fusing all available data, it is crucial to present this information to the pilot in a convenient way. A well-designed system improves the pilot's situational awareness and decreases workload. As shown in Fig. 1, the state-of-the-art solutions use either a panel-mounted display (PMD) or a see-through head-worn display (HWD), also known as augmented reality (AR) display. An example of the former is the integrated cueing environment (ICE) by the US military,[4,5] while the latter approach is adopted by, for example, Münsterer et al.,[6–8] Schmerwitz et al.,[9] and Viertler and Hajek.[10] Both methods have shown their benefits in many studies. PMDs can use full-color, high-resolution flat panel screens to present information in many different ways. Even egocentric views with a field-of-view up to 360 deg have been implemented on such displays.[11] A see-through HWD offers a way to visually integrate information in the pilot's out-the-window view. Conformal display symbology such as tunnel-in-the-sky or obstacle cues has been found to increase performance and safety in several scenarios.[12]

Nevertheless, both PMDs and AR HWDs still suffer from several limitations. To overcome the weaknesses of the two conventional display methods, we investigate the advantages and drawbacks of using a non-see-through, immersive HWD as display device. The idea is to combine strengths of existing PMD- and AR-based enhanced/synthetic vision solutions and to overcome weaknesses of the established display systems by using this alternative display medium. As shown in Fig. 1, the proposed display concept is based on the same data acquisition via sensors and databases.

This contribution presents the details of our concept, called Virtual Cockpit (VC), as well as its expected advantages and challenges to be met (Sec. 3). Furthermore, our development and simulation environment for various types of current AR and virtual reality (VR) goggles is introduced (Sec. 2). It is based on the game engine Unity and was designed as a flexible software suite for rapid prototyping

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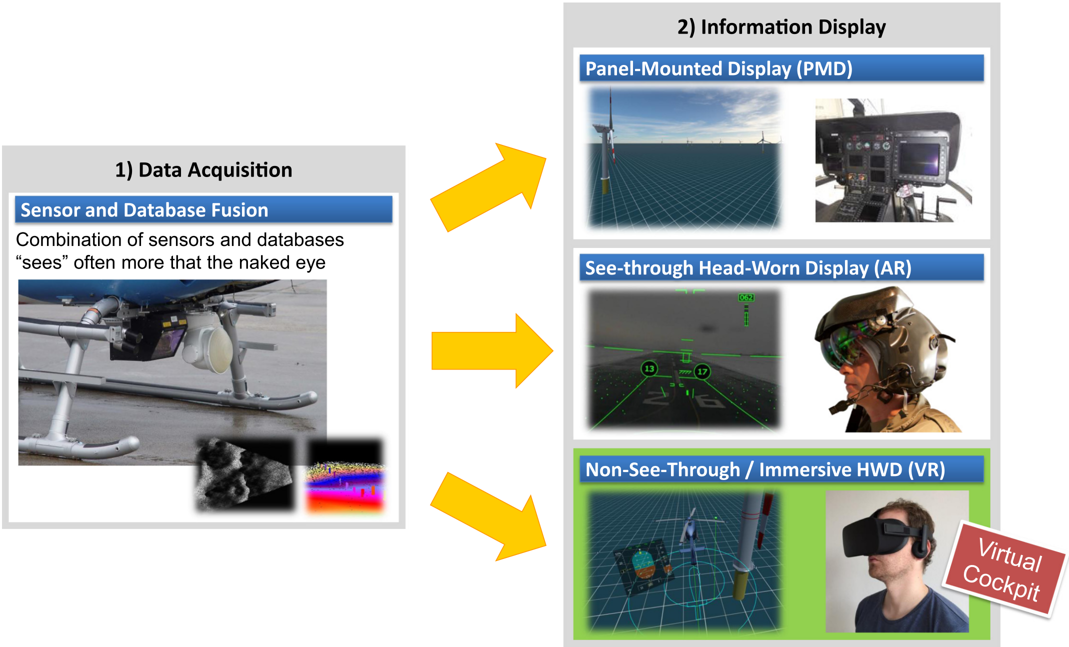

Fig. 1 Overview of visual assistance systems for helicopter pilots flying in DVE.

and testing of symbology concepts. Sections 4 and 5 show two concrete implementations of the VC. By means of two human factors studies, the potentials of the developed symbologies are evaluated. The first study compares several synthetic representations of the ocean surface, which shall improve usable visual cues in helicopter offshore scenarios. The second experiment evaluates the usefulness of three-dimensional (3-D) perspective exocentric views. The paper is summed up with a conclusion and an outlook on future work in Sec. 6.

The paper is based on a number of published conference papers.[13–18] Here, a detailed description of our development and simulation environment as well as an extended statistical analysis of the experiments are added. Moreover, the paper combines our main findings, draws overall conclusions, and outlines future directions for the VC research.

2 XR Simulator: a Flexible Simulation Environment for Head-Worn Augmented and Virtual Reality Displays

The first operational, integrated helmet-mounted display (HMD) for helicopter pilots—the integrated helmet and display sighting system—has been used on the AH-64 Apache since the early 1980s.[19,20] Today, companies such as Microsoft or Oculus VR advance such technologies and bring them to the consumer electronics market. Recent technical advancements give reason to predict wide usage of such devices also on civil flight decks. Arthur et al.[21] presented several potential applications for that. To conduct human factors evaluations of AR and VR display concepts, we built a flexible development and simulation environment, which is introduced in this section.

2.1 *Game Engine Unity: a Flexible Development and Simulation Solution*

The first major goal for the implementation of the XR simulator (XRSim)—where X acts as a placeholder for A(ugmented), V(irtual), and M(ixed)—was to integrate various consumer-grade AR and VR HWDs. Besides the lower hardware costs, such devices usually require less integration efforts and can be used in an office or low-fidelity simulator setup. Expensive, flight-proof HWDs are often less available and more complicated to use. Consequently, researchers can use consumer-grade devices to develop and test display concepts within an easy-to-use environment before porting them to flight-proof hardware for further evaluations.

The second major goal was to create a display software development environment that allows for fast and easy symbology prototyping and testing. For research purposes, it is crucial to have a toolbox that allows the researcher to rapidly realize and test their symbology ideas.

To achieve these goals, the game engine Unity[22] was chosen as the software tool for implementing the graphics to be displayed on the HWDs. Unity comes with an integrated development environment (IDE) that simplifies the process of generating the display symbologies and scenes for human factors evaluations. With a few mouse-clicks in the graphical 3-D editor, the user can create or import new objects and place them within a 3-D world. Moreover, the programmer can write C#-scripts to add functionality. Finally, Unity comprises many readily available modules and packages that strongly facilitate the fast implementation of virtual environments. An important plus is that Unity's XR module hides hardware-specific differences between the AR/VR goggles from the programmer. Thus, no changes to the display code are required when the display hardware is changed. Unity supports many consumer-grade VR and AR devices such as Oculus Rift, Meta 2, or Microsoft HoloLens. This makes it an attractive choice for the development of software targeting such devices.[17,18]

2.2 *System Architecture of the XR Simulator*

Figure 2 shows the architecture of the assembled XRSim and gives an overview of the hardware components, the various

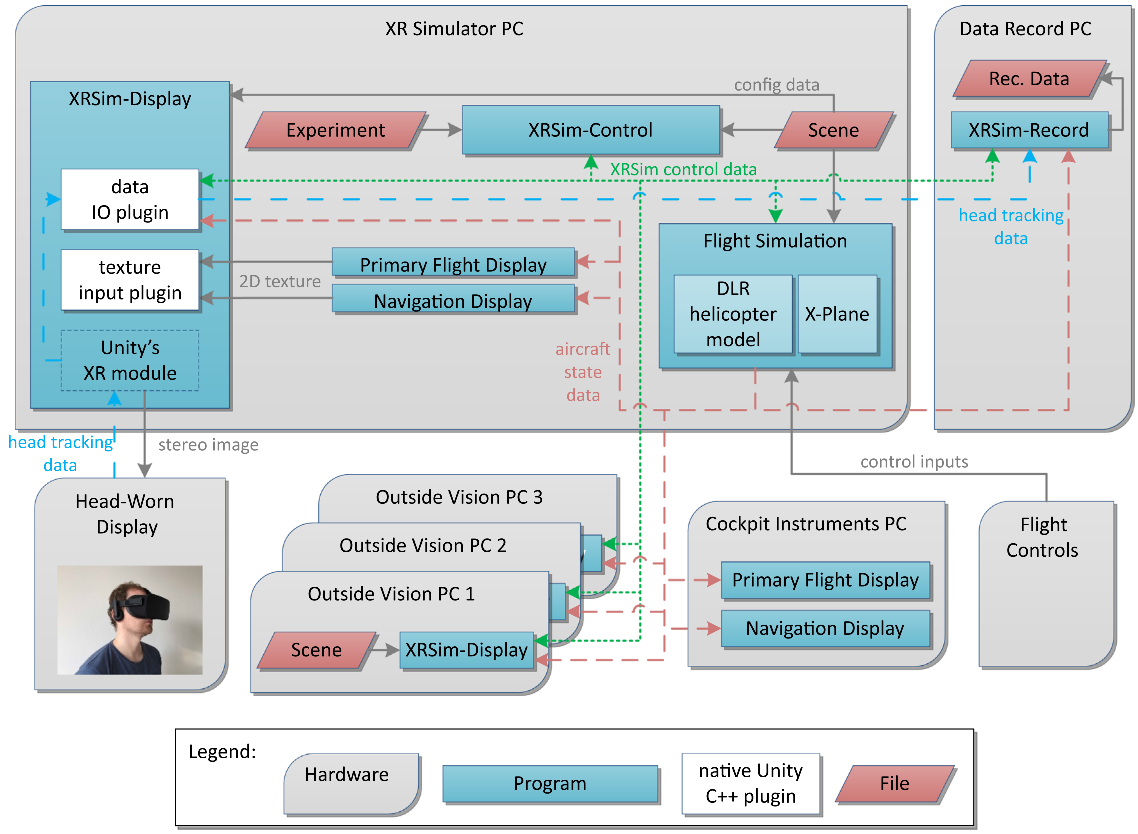

Fig. 2 Architecture of the VC simulation environment XRSim.

software applications, and the data flows between the modules. The system comprises a conventional, fixed-base helicopter simulator with outside vision system, flat-panel cockpit screens, and professional, active force feedback flight controls. The heart of the system is a workstation PC running the flight simulation, the XRSim-Control application, and the XRSim-Display module. The latter is connected to the HWD unit. Finally, a separate PC handles the recording of aircraft state and head-tracking data.

The flight simulation computes and transmits the current aircraft state (red lines) to all display applications and the XRSim-Record program. The Unity-based XRSim-Display software uses this data together with the head-tracking input (blue lines) to generate a stereo image to be displayed on the HWD. All communication with the HWD is implemented by Unity's XR module, which supports a wide range of commercially available VR and AR goggles. In addition, our flight-proof HWD—the Elbit JEDEYE™—can be connected via in-house software. Several instances of the XRSim-Display module can be run on the outside vision PCs to display the scenery on the projection screen of our helicopter simulator. While this is not required with non-see-through VR goggles, it is essential for generating the far domain in AR applications and for experimental baseline testing with a conventional cockpit.

The XRSim provides two options for the flight simulation. First, the commercially available software X-Plane can be used to simulate the behavior of several existing helicopter types. Second, a custom-made model of our EC135 research helicopter with advanced flight control modes is available. This command model was developed by the German Aerospace Center (DLR) and provides various upper modes to ease piloting the helicopter.[23] For example, selecting height hold and vertical velocity command for the collective enables the pilot to directly command a vertical speed via the collective. If the collective remains in the neutral position, the helicopter stays at the current altitude regardless of any cyclic stick inputs.

The setup and procedure of an experiment is managed by XRSim-Control. It reads the experiment and scene configuration data from two files and sends commands to all involved applications. Furthermore, it provides a graphical user interface for the experiment leader. As sketched by the green lines in Fig. 2, this module communicates with several involved programs to manage the correct procedure of the experiment. When the experiment leader starts the next trial, for instance, XRSim-Control tells the display modules to load the appropriate scenario. After reconfirmation, it requests the recorder and the flight simulation to start the run.

2.3 *Compatibility with Existing Simulation Infrastructure and Integration of Legacy Display Code*

Aircraft state, head-tracking, and XRSim control data are exchanged between the modules via shared memory and Ethernet using the UDP protocol. For compatibility, the VC simulation environment uses the same data interfaces that are used by our flight-proof HMDs in the high-fidelity simulator and in our research helicopter. In the XRSim-Display program, this data input/output module is implemented via Unity's native plugin mechanism. This allows us to call existing C++ functions, defined in externally compiled dynamic-link libraries, from C#-based Unity scripts.

Finally, we developed a mechanism to integrate externally rendered cockpit instruments into the 3-D scene generated by the Unity-based XRSim-Display. These so-called virtual cockpit instrument (VCIs) are two-dimensional (2-D) displays that are virtually placed at a fixed location relative to the aircraft-fixed reference system. They can be imagined like virtual flat-panel screens located in the synthetic 3-D world. An example of such a VCI is the primary flight display (PFD) used in the study described in Sec. 5 (Fig. 8).

As the graphics of these cockpit displays have already been implemented for conventional cockpit monitors, we wanted to reuse the existing OpenGL code without implementing the displays again within the Unity game engine. To do so, the legacy source code is modified to render into a framebuffer target, which is then transferred into a shared memory. A texture input plugin in XRSim-Display reads this pixel data and updates a textured quad element, which represents the VCI. Although the transfer of this 2-D texture introduces small latencies, this lag is not noticeable by the user. Implementation details are described in Refs. 17 and 18. In Fig. 2, the method is exemplarily sketched with a PFD and a navigation display program generating two VCIs for XRSim-Display.

2.4 *Using the XR Simulator for Human Factors Evaluations*

The described system can be used for human factors evaluations in different ways. For certain experiments, the simulator can serve as a replacement for a conventional cockpit simulator. By using a VR system such as the Oculus Rift, a fully immersive cockpit environment can be created. Thereby, part-task studies or procedure trainings can be conducted with a simple setup without the need for an outside vision system, real cockpit hardware, or an aircraft cell. The whole evaluation scene is provided by the VR goggles. For instance, Schmerwitz et al.[24,25] used such a simple part-task setup to evaluate conformal landing symbologies for DVE. Oberhauser et al.[26] applied a similar setup in the early phase of the cockpit design process.

For more advanced studies, one can use the full system including outside vision, cockpit instruments, and flight controls. With this configuration, various consumer-grade AR and VR goggles can be integrated into a conventional cockpit environment. Figure 3 shows such a setup. Both studies described in Secs. 4 and 5 use the depicted configuration with the Oculus Rift CV 1. These VR goggles feature two OLED image sources with 90-Hz refresh rate and a resolution of 1080×1200 pixels per eye. The diagonal field of view (FOV) is ~110 deg. The head pose is measured by optical and inertial tracking systems.

In summary, the XRSim is a powerful simulation environment designed for rapid implementation and evaluation of AR- and VR-based display concepts. By using consumer-grade display devices and the game engine Unity, we were able to reduce hardware costs and simplify the development and testing process of new symbologies. Moreover, several techniques were devised to integrate the Unity-based system with the hard- and software of DLR's existing simulation facilities. A weakness of the current setup is that the pilot's interaction with the real and the virtual environment is limited. If required for future experiments, advanced methods such as finger-tracking[27] should be integrated.

Fig. 3 Pilot wearing the Oculus Rift goggles in the VC simulator.

3 Virtual Cockpit: a Head-Worn Display Concept for Degraded Visual Environments

As described in Sec. 1, our VC concept uses a non-see-through HWD as an alternative to the two conventionally used display types (PMD, see-through HWD).

3.1 *Concept and Expected Benefits*

Figure 4 shows a high-level overview of the proposed display concept. The stereo image displayed on the HWD comprises two view domains depicted as blue rectangles. First, an external view domain provides an artificial representation of the surroundings that replaces the pilot's natural out-the-window view. It is comparable to enhanced, synthetic, and external vision systems (EVS, SVS, XVS) as it incorporates data from terrain and obstacle databases, from aircraft-mounted sensors and from various other sources (e.g., traffic, weather). The generated picture of the surroundings is under many DVE conditions superior to what the pilots see with their naked eyes. Second, flight guidance and additional information is conveyed via visual conformal symbology and VCIs. Conformal symbol sets such as tunnel-in-the-sky are a well-established way of presenting flight guidance and obstacle information in AR displays.[12] As described in Sec. 2, VCIs can be imagined like a virtual version of conventional flat-panel screens displayed at a fixed location in the synthetic view. More information about this concept can be found in Ref. 28.

The main difference between the established systems and our concept is the display medium. By using an immersive

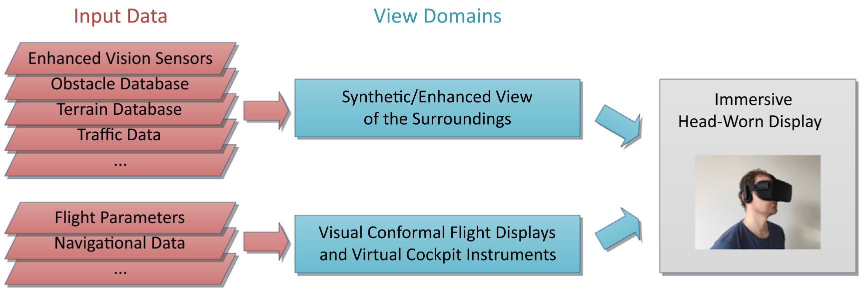

Fig. 4 Concept of the VC based on an immersive HWD.

HWD, limitations of established systems shall be overcome while keeping advantages of existing solutions. VR goggles are closely related to AR glasses, which means that we can retain major benefits of state-of-the-art HWD solutions. Via head-tracking the synthetic scene is always aligned with the occluded reality. This is expected to feel natural and intuitive since pilots can look around in the virtual environment as they are used to when orienting themselves under good visual conditions without HWD. Instead of a degraded out-the-window view, they see a synthetic external view. The immersive, head-tracked view is a great advantage over PMDs, which can only show a downscaled, 2-D projection of the 3-D scene. Further, established approaches from AR display design can be transferred. For instance, visual conformal representations and scene-linked display elements can also be implemented in the VC environment.

Compared to its see-through counterpart, an immersive HWD gives us full control of what the pilot sees. With conventional, transparent HWDs, the displayed symbology is always superimposed on the natural view of the surroundings. This can lead to various problems. For example, the symbology might be unreadable in bright environments or undesired interferences between real and synthetic domain may mislead the pilot's visual perception. Our previous work revealed the latter to be especially problematic with VCIs as they visually interfere with the real cockpit environment behind.[29] In addition, the swirled-up particles during brownout landings can create false external motion cues and cause spatial disorientation. By design, an immersive display avoids these adverse influences of the reality. Further, VR devices usually offer a wider FOV and are able to display full-color symbology with high contrast and color saturation.

Like conventional cockpit instruments, VCIs provide information such as flight parameters, navigation data, or aircraft systems status. However, VCIs are more flexible than a state-of-the-art cockpit. They are location-independent and can take various shapes and forms, from a simple virtualization of conventional head-down instruments to a completely redesigned layout making full use of the extended opportunities. Using this flexibility, one could create adaptable cockpit layouts that are designed for a specific task. Then, pilots could, for instance, switch between a "landing cockpit" and a "hover cockpit," both providing the relevant information in the best way for the current task.

Based on images from a distributed aperture system aperture system, an unrestricted outside view can be presented on the HWD. This allows the pilots to virtually see through the aircraft structure. If enough information is available, the display can also offer a synthetic, 3-D overview of the situation around the aircraft from a modifiable third-person viewpoint or from the perspective of an escorting unmanned aircraft system. This can be used to assess the tactical situation in military maneuvers or to provide a better overview of the surroundings in confined areas. Such an approach is presented and evaluated in Sec. 5.

3.2 *Limitations and Challenges*

The application of VR goggles entails several challenges to be met and current technology still has technical limitations that need to be taken into account. Since the presented information will be perceived by the pilot's eyes, the properties of the display should be compared with the capabilities of the human visual system. This involves many aspects such as resolution, FOV, brightness, contrast, and several more, which can not all be examined in this paper. Melzer and Moffitt[19] provided a thorough discussion of the factors to be considered. Here, angular or spatial resolution as one important issue is exemplarily discussed.

High spatial resolution is required for the pilot to see small and distant objects in the far domain as well as to recognize details and read alphanumeric information of the symbology in the near domain. A human with normal visual acuity, often referred to as $20/20$ vision, is able to resolve one arc minute ($1/60$ deg),[30] which would require a pixel density of 60 pixels per degree (ppd). However, this value only gives a rough guideline as many humans have better than $20/20$ vision and hyperacuity allows us to discriminate details up to 10 arc seconds in certain constellations. Bailey et al.[31,32] tested these theoretical values in a flight test campaign of an XVS, which should fully replace the pilots' natural out-the-window view by cameras and monitors. They concluded that their system with 63 ppd and $51\ \text{deg} \times 30\ \text{deg}$ FOV did not achieve equivalent visual capability in see-and-avoid and see-to-follow scenarios. Nevertheless, earlier work showed that self-navigation is still possible even with severely restricted FOV[33] and resolution.[34]

The design of HWD devices requires a trade-off between angular resolution and FOV of the generated image. This is also known as the FOV/resolution invariant. The image source has a certain number of pixels, which are magnified by the optical system to cover a certain area of the users view. Increasing this area, called the FOV of the HWD, results in larger pixels and lower angular resolution. Current consumer VR goggles choose FOV over angular resolution to create a feeling of immersion and presence. For instance, the Oculus Rift CV1 features two 1080×1200 image sources and $\sim$110-deg diagonal FOV. This results in an angular pixel density of around 12 to 13 ppd. This is only an approximate value because the optics may not distribute the pixels equally over the FOV and the individual lens to eye distance influences the involved parameters. For comparison, the Elbit JEDEYE™, a flight-proof HWD, offers around 27 ppd having a total FOV of 80 $\deg \times 40$ deg with 2200×1080 resolution (60-deg binocular overlap). For a hypothetic HWD with 100 $\deg \times 100$ deg FOV per eye, 6000×6000 px are required to reach a density of 60 ppd. However, such high pixel density over the whole display is actually not needed because only the fovea has this high visual acuity. Hence, decreasing the pixel density from the center to the peripheral display areas and foveated rendering solutions[35] are interesting approaches for improved future systems.

Two aspects are important for the interpretation of these calculations. First, even though current VR goggles do not reach human eye capabilities in optimal viewing conditions, they may still perform better than the naked eye in many DVE situations, which is the targeted scenario of the VC. Unfortunately, no single value for unaided visual acuity in DVE exists as the term includes a wide range of adverse environmental conditions. To get an idea, one can consult Fenley et al.,[36] who provided an overview of DVE operational levels and relate the ADS-33 usable cue environment (UCE) levels to approximate Snellen acuities (UCE $1 < 20/50$, UCE $2 < 20/80$, and UCE $3 > 20/80$). The second important aspect is that the VC is not intended to show raw sensor imagery but a computer-generated picture of the environment. This implies that various data from sensors and databases can be fused to generate an enhanced picture of the situation. The pilots will then see a virtual scene with good visual conditions and cueing of sensor-detected obstacles and targets. In such a setup, the resolution requirements for the display hardware are certainly lower than in setups where the pilots have to detect low-contrast objects on the raw imagery by themselves. For example, the camera-based sense and avoid system by Minwalla et al.[37] transfers the traffic detection task from the pilot (see Bailey et al.[31]) to the sensor system and thereby exceeds the typical visual acquisition ranges. If such a system can display intruder positions in the synthetic outside view on the HWD, a high-definition image source may not be required.

In conclusion, current technology is neither capable of displaying a visually equivalent out-the-window view on the HWD nor can the angular display resolution keep up with conventional cockpit screens. Despite that, it is very important to note that a high-resolution XVS display may not be required if an equivalent or better level of performance and safety can be reached with suitable sensor hardware and software. The currently achievable quality appears to be sufficient for certain applications and current research activities promise higher capabilities in the near future.

Another important issue is the pilot's ability to interact with the cockpit environment. In our immersive setting, the pilot is not be able to directly see the real surroundings, which implies that virtual representations of important elements such as the flight controls may be required. In addition, the pilots may also need to interact with the virtual environment. The degree of required interaction capabilities strongly depends on the application. For simple tasks, the available input elements on the cyclic stick may suffice. For more complex human–computer interaction, hand-/finger-tracking, eye-tracking, and voice-commands could be integrated. First concepts and experiments with such input modalities are described by Furness,[38] Thomas et al.,[39] and Aslandere et al.[27]

In summary, many issues must be solved to complete a VC which can replace a conventional flight deck in the long-term. Of course, due to the very importance of this vision system, a sufficient technical reliability has to be achieved and proven as well as failure procedures must be established.

3.3 *Application to Helicopter Offshore Operations*

In this paper, we apply the VC concept to helicopter offshore operations. Helicopters play an important role during both construction and operation of offshore wind farms, which are rapidly growing in recent years. Due to their flexibility, their hover capability, and their higher speed compared to ships, these aircraft perform important tasks such as HEMS as well as passenger and freight transfer flights. The missions often include demanding platform landings and hoist operations to drop off workers onto wind turbines. By means of an online survey and a structured interview with pilots and operators, we analyzed the specific challenges of such operations.[14] In summary, we identified two major issues: (1) a lack of usable outside visual cues and (2) a restricted external view, which is particularly unfavorable when operating close to obstacles. The former issue originates from adverse weather conditions and from only few fixed reference objects being present in this environment. In addition, the moving waves of the ocean surface often provide more misleading than valuable information. The restricted external view is often caused by nontransparent parts of the aircraft structure but is in certain scenarios also a result of the pilot's inappropriate viewpoint. In general, pilots can hardly see threats below, above, and behind the helicopter. Our full analysis of helicopter offshore operations can be found in Ref. 14.

The approach taken by our VC environment offers the potential to tackle these issues. The missing outside visual cues can be simply generated since the whole presentation of the surroundings is in the hand of the display designer. Thus, a sensor-based view can be overlaid with appropriate cueing symbology or a full synthetic view with the required cues can be displayed. An unrestricted view of the surroundings can be generated by virtually making the airframe transparent or by showing the situation from a third-person view. The following Secs. 4 and 5 will introduce and assess two exemplary VC implementations addressing the two identified issues.

4 Creating Usable Visual Cues with the Virtual Cockpit: a Synthetic Ocean Surface Representation

This section shows how the lack of outside visual cues in an offshore scenario can be prevented in the VC. The goal of this work was to find a synthetic representation of the ocean surface that is more valuable for the pilots than the natural appearance of the sea. The developed symbol sets are evaluated with a human factors study in the XRSim (see Sec. 2).

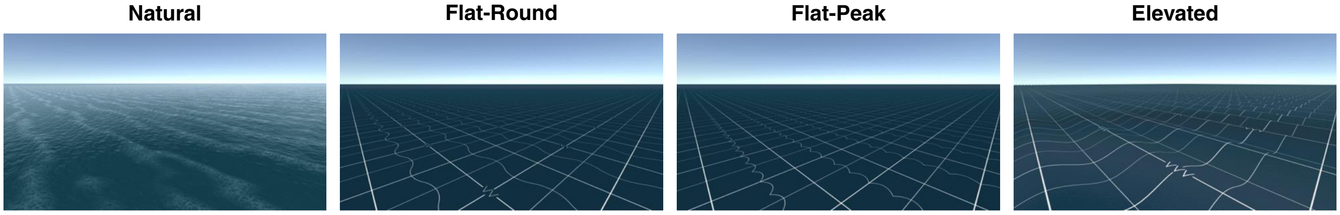

Fig. 5 Developed ocean surface representations with wind coming from around 45 deg (from the right back to the left front in the images).

4.1 *Display Concept and Related Work*

Onshore pilots flying under visual flight rules can orient themselves by looking out the window. The horizon, various objects, and terrain features help them to judge their position and attitude. The offshore environment, however, offers only few usable outside visual cues. First, only few fixed objects exist. Second, usable optical flow and ground texture cues are rarely available from the water surface. Caused by its own movement, the sea often provides more misleading than valuable information. Third, this shortage of external references is often even aggravated by weather conditions that further degrade the view and obscure the horizon. This lack of cues results in false height and distance estimates. Thus, offshore flying and maneuvers like hovering and holding the helicopter position become a highly challenging task.

Moreover, it is essential for a pilot to know where the wind is coming from and how strong it is, because the wind strongly influences the performance of the helicopter. If at all possible, landings are conducted with headwind. Experienced offshore pilots can estimate wind direction and speed from the shape of the sea surface. Under calm wind conditions, the water looks like a mirror. At higher wind speeds, larger waves with spray appear and foam streaks move in the wind direction.

The representation of the ground surface in synthetic and enhanced vision displays has been researched extensively in past decades. However, the main focus has been placed on the illustration of onshore environments and mountainous terrain in particular. In general, one has to distinguish between terrain representations for see-through HWDs[6] and symbologies for PMDs.[4,5,40] The former usually are monochrome and designed as an overlay for the natural out-the-window view of the pilot. This poses specific requirements to allow the pilots to still see the reality through the symbology and to avoid clutter. In contrast, symbologies on PMDs have no see-through requirements and can make use of full-color screens. A very common approach in literature is a grid symbology superimposed onto the terrain. Non-see-through displays also often apply various types of textures.

Here, the goal was to develop a synthetic representation of the ocean surface that replaces the real sea and additionally includes more valuable information. Based on the analysis above, the display concept should provide: (1) usable visual references for the pilots to better perceive their motion and (2) information about wind direction and speed.

We developed four symbology variants for immersive HWDs as part of the VC concept. The goal was not to get the graphics as similar to a real sea surface as possible. Instead, we wanted to create computer-generated representations that improve the pilot's ability to fly over open water. All graphics were implemented with the Unity game engine described in Sec. 2.

As shown in Fig. 5, the first symbology—called "Natural"—is strongly influenced by the appearance of the real sea. The others are more abstract representations. Their degree of abstraction varies from uniform, wave-like 3-D-meshes called "Elevated" to simple, flat surfaces with special grid structures ("Flat-Round" and "Flat-Peak"). All variants have in common that they are static, which means that no moving waves are presented. This reduces clutter and provides a fixed visual reference for the pilots to perceive drift motions. The synthetic water surface is positioned at sea level, where the pilots would see the real ocean surface in good visibility without wearing the immersive goggles. Further, all representations show the wind force in four discrete levels corresponding to certain wind speed ranges.

The Natural representation incorporates elements from real water but only to a certain degree. It comprises waves and the typical water reflections and refractions. This follows the idea that the pilots should intuitively perceive the wind characteristics via the familiar appearance of the water. However, the waves are static so as to prevent adverse visual motion cues.

The Flat-Round display variant is a modified regular grid. The water surface is represented by a flat blue-colored surface. The grid lines are oriented parallel (and perpendicular) to the wind direction. Every second grid line perpendicular to the wind is replaced by a wavelike line. Regularly spread arrowheads point in the direction of the wind. The wind force is conveyed via the number of arrowheads. In addition, the amplitude of the curvy line is increased and the wavelength is reduced for stronger winds.

Flat-Peak is related to Flat-Round as it is also based on a flat surface with a regular grid overlay. However, the arrowheads and the sinusoidal line are replaced by an undulated line with peaks on one side. The peaks indicate the wind direction such as the arrowheads do in the flat-round design. The wind strength is shown by the number of the peaks and the amplitude of the "wave"-line.

In contrast to the other layouts, the Elevated design is not flat. It is made of a 3-D mesh with a uniform and steady wave structure. Moreover, the display comprises a regular grid oriented with the wind direction. The wave crest lines are straight and run perpendicular to the wind direction. The arrowhead symbology used by Flat-Round is also applied in this display variant to show wind direction and strength. In addition, the wave height increases with the wind speed.

4.2 *Study Method*

To assess the value of the developed display concepts, an experiment was conducted in the XRSim.

4.2.1 *Participants*

Nine male pilots with an average age of 36 (range from 25 to 60) participated in the study. Six subjects flew both military and civil aircraft while three had civil background only. The mean flight hours of all subjects was 2236 h (min: 215 h, max: 6200 h). Regarding licenses, two owned a private pilot license (PPL), four a commercial pilot license (CPL), and three an airline transport pilot license (ATPL).

4.2.2 *Apparatus*

The experiment took place in the XRSim using the Oculus Rift CV 1 (for details see Sec. 2). The outside vision system and the cockpit instruments were switched off as the pilots were fully immersed in the virtual environment created by the VR goggles during the whole testing. To place the focus on the symbology evaluation, not on the flying task, we used our in-house developed command model with automatic flight control system (AFCS) as flight simulation.[23] This allows us to apply various command types and hold modes to the four flight control axes. In the chosen setup, the axes were uncoupled. The pilots could directly control the altitude via the collective and set the airspeed via the longitudinal cyclic axis. Turns were commanded with lateral cyclic inputs while the pedals were not required at all. The impact of the wind was intentionally not eliminated by the control system. Thus, the wind conditions caused the aircraft to drift in crosswinds and to lose ground speed when turning into the wind.

4.2.3 *Experimental design*

The experiment applied a within-subject design with two independent variables: (1) display type (Natural, Flat-Round, Flat-Peak, and Elevated) and (2) wind condition. The wind variable had four levels represented by the wind speeds 0 knots, 8 knots, 20 knots, and 35 knots (each combined with a random wind direction). This resulted in a total of 16 experimental conditions per pilot (four displays $\times$ four wind conditions). The four flights with the same display condition were flown in a row. In total, 144 flights (9 pilots $\times$ 16 conditions) were performed for this evaluation. The whole test session including briefing, training, testing phase, and debriefing lasted around 3 h.

4.2.4 *Symbology*

During the whole experiment, no flight instruments except for the developed ocean representation were available. The pilots had an unobstructed view of the surroundings without any cockpit structure displayed around them. Also, the only object in the synthetic environment was the offshore landing deck during the approach scenario. This implies that the ground speed estimation during the first segment could only be based on the water representation. For the approach task, pilots could use both water symbology and the offshore platform to manage their glide path and speed. Further, no virtual representations of the flight controls or other real cockpit elements were displayed.

4.2.5 *Task*

Each flight was split into two parts. The first segment was started in-flight, 500 ft over water with 60 knots ground speed. Pilots were instructed to: (1) judge the wind direction based on the water representation, (2) turn the helicopter into the wind, and (3) adjust the airspeed to maintain 60 knots ground speed when turned into the wind. The second segment was an approach to an offshore platform. Pilots had to perform a 90-deg turn into the wind and conduct a straight approach.

4.2.6 *Data analysis*

The data analysis was carried out with MATLAB[41] and the statistical computing environment R.[42] An α level of 0.05 was adopted for significance.

4.3 *Study Results*

The pilots were asked to turn the helicopter against the wind while reading the wind direction from the presented symbology. To analyze the measured deviation from the desired "headwind-heading," a two-way repeated-measures analysis of variance (ANOVA) with the independent variables symbology type and wind condition was performed. No significant main or interaction effects on the heading accuracy were found.

For further assessment, the obtained data were classified into four groups. If the pilot deviated less than 2 deg, the flight was categorized as "desired." Deviations up to 10 deg correspond to "adequate." "Front-back" represents flights where the pilots turned not into but out of the wind and flew a heading directly opposite of the desired direction with tailwind. The graphs in Fig. 6 show that Natural achieved fewer results in the "desired" range than the other display types. In addition, more "out of bound" flights were observed under this condition. Flat-Round and Elevated seem to be relatively equal as both generated at least 89% "desired" flights. Interestingly, the Flat-Peak variant also had a high number of "desired" and "adequate" flights but showed a number of front-back confusions.

In addition, the pilots were instructed to adjust the airspeed to maintain 60 knots ground speed when turned into the wind. As no flight instruments were displayed, pilots had to judge the speed visually from their motion relative to the ocean surface representation. The obtained deviations from the desired ground speed were spread between -50 knots (too slow) and $+77$ knots (too fast). On average, pilots flew faster than desired and nearly half of the flights produced deviations larger than 15 knots. Similarly, the participants had problems managing their speed during the approach to the offshore platform in the second segment of the flight. A repeated-measures ANOVA revealed no significant influence of the display type but a significant main

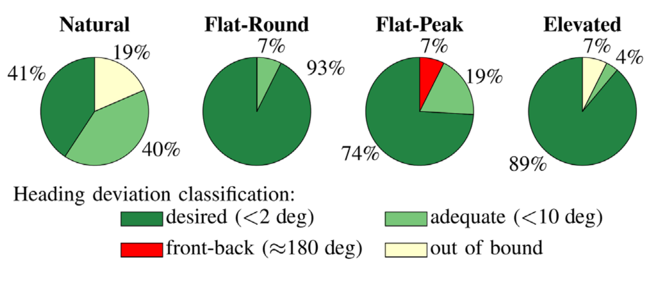

Fig. 6 Accuracy reached when turning against the wind based on the developed ocean surface representations.

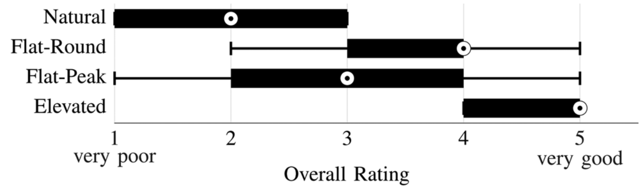

Fig. 7 Overall rating of the developed ocean surface representations. Boxplots show median (circle), 25th and 75th percentiles (bar) with whisker length 1.5 IQR.

effect of the wind condition, $F(2, 16) = 6.151$, $p = 0.010$, and $\eta^2 = 0.146$. The data show smaller speed deviations for lower wind speeds. However, *post hoc* tests could not confirm this finding.

Figure 7 shows the pilots' overall rating of the developed ocean surface representations. A repeated-measures ANOVA revealed significant differences of the overall rating between the four ocean surface representations, $F(3, 24) = 17.435$, $p < 0.001$, and $\eta^2 = 0.554$. Tukey *post hoc* tests showed that Natural was perceived significantly poorer than all other variants (Flat-Round: $p < 0.001$, Flat-Peak: $p = 0.009$, and Elevated: $p < 0.001$). In addition, Elevated was rated significantly better than the other variants (Flat-Round: $p = 0.025$, Flat-Peak: $p < 0.001$).

Other results from the debriefing questionnaire show the same tendencies as the overall ranking. Flat-Round and Elevated were rated best regarding their support in estimating wind speed and direction as well as in performing the flight task. Elevated was rated as most intuitively understandable and was perceived to best increase situation awareness. The height and orientation of the waves in this design was acknowledged as a clear indication of the wind conditions. Flat-Peak and its wavy line was rated not intuitive by many participants as it could be interpreted as wind from both perpendicular directions. Natural was not perceived to be helpful because both wind direction and speed were hard to assess. All but one pilot agreed that displaying wind direction and speed via a grid symbology is useful. Moreover, one pilot remarked he requires the wind speed as a number while other participants said that the approximated/discrete strength indication via number of arrows is sufficient. Finally, all participants rated the XRSim as good. They agreed that a virtual representation of the flight controls and the own hands was not required for this task.

4.4 *Study Discussion*

Recalling the two goals for the symbology development defined above, it must be discussed if the tested design adequately provided: (1) usable visual references for the pilots to better perceive their motion and (2) information about wind direction and speed.

Regarding the latter, statistical tests could not identify significant differences between the symbology variants. Despite this, a closer look at the data in terms of heading accuracy classification revealed important issues leading to the conclusion that all three abstract display variants (Flat-Round, Flat-Peak, and Elevated) are favored over the Natural layout. This is also confirmed by the subjective results. With all abstract variants, the pilots could turn into the wind very precisely. However, Flat-Peak was found prone to "front-back-confusion." That is that the pilot interprets the symbology as wind coming from the back while in fact he flies into the wind. It has to be noted that the pilots often realized an initial misinterpretation during the flight and corrected before the end of the task. Thus, the actual number of initial front-back confusions was higher. The questionnaires indicate a clearer advantage for the Elevated symbology than the objective results. Pilots liked the emphasized and intuitive presentation of the wind information via height and orientation of the waves. However, this representation is visually very compelling and might unnecessarily draw attention. As Flat-Round achieved the same objective performance with a much simpler design, this might be the better option if one aims for a representation that is "as easy and simple as possible."

Regarding usable visual references for motion perception, the abstract grid representations also outperformed the Natural display. Several pilots stated that they not only estimated the wind direction and speed based on the presented symbology, but also based their decision on the wind-induced drift of the helicopter. The grid served as a fixed reference on ground, which is usually not available over water. This made it easy to visually recognize even small drift velocities caused by side-wind components. Thus, pilots could judge the wind direction just by observing the behavior of the helicopter relative to the static ground representation, without interpreting the arrows of the symbology. In conclusion, a grid even without additional wind indications will still be very helpful.

Even though the grid drastically improves the perception of drift motion, it seems not to be sufficient to judge the own ground speed. None of the tested symbologies enabled the pilots to maintain 60 knots after turning into the wind. However, one can argue that in a real scenario the pilots would have additional air- and ground-speed indications providing them with exact values during approach. Another factor that might have impaired the speed estimation is the missing peripheral vision as the Oculus Rift provides only around 100 deg of horizontal FOV, which leaves about 50 deg on both sides occluded and black. These outer areas of the human vision play an important role in the perception of speed.

Further graphs and more detailed descriptions of the experiment are presented in Ref. 15.

5 Increasing Spatial Awareness with the Virtual Cockpit: 3-D Ego- and Exocentric Views

In Sec. 3.3, two major problems for offshore helicopter pilots are identified: (1) a lack of usable outside visual cues and (2) a restricted external view. The study described in the previous section presents an approach to mitigate the first issue. Here, the focus is on the latter aspect. The described work assesses if 3-D ego- and exocentric views displayed on an immersive HWD have the potential to increase spatial awareness in situations with restricted external vision.

Egocentric means that the displayed viewpoint and frame of reference conform with the pilot's real location and orientation. In simple terms, an egocentric view is what the pilot sees when sitting in the cockpit seat. By contrast, an exocentric view depicts the situation from a viewpoint different from the pilot's physical location. The chase-cam view often presented in car racing video games is a well-known example for this type of view.

3-D ego- and exocentric display perspectives have been thoroughly discussed in research on synthetic vision navigation and PFDs. Costs and benefits of different viewpoints and perspectives are well documented.[43,44] However, previous research on exocentric views deals with head-down display representations, whereas the proposed approach covers head-tracked HWDs. Moreover, this work places the focus on helicopter-specific tasks such as hover and land in close proximity to obstacles.

5.1 *Display Concept*

Four 3-D perspective views were developed for the VC. An overview of the symbologies is given by Fig. 8. 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. 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. The main feature of Exocentric-Base and Exocentric-Trans is that the pilots are virtually taken out of the cockpit to an exocentric viewpoint behind and above the helicopter. This chase-cam view provides the pilots with a sight of the whole space around their helicopter. Accordingly, these symbologies are expected to improve spatial awareness. Both view types are mostly similar except for the helicopter being transparent in Exocentric-Trans. This is to obscure objects ahead of the helicopter as little as possible. 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' FOV when they alter the pitch angle.

Each 3-D perspective view is equipped with a standard 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. Cockpit-Base as the experiment baseline has no additional assistance features. The other three perspective view displays are enhanced with visual conformal symbology. The advantages of such a scene-linked overlay have been shown for AR displays.[12] Here, this technique is applied to enhance the judgment of the helicopter position and distance relative to the surroundings. As explained by Wickens,[44] 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. 8, 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 shown in Fig. 8. This symbology is projected onto the target hover height. 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. Moreover, the ocean surface of the synthetic vision is represented by the grid symbology presented in Sec. 4.

5.2 *Study Method*

The main objective of our simulator study was to gain insights if different 3-D perspective views presented on immersive HWDs 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 impact on workload and situation awareness.

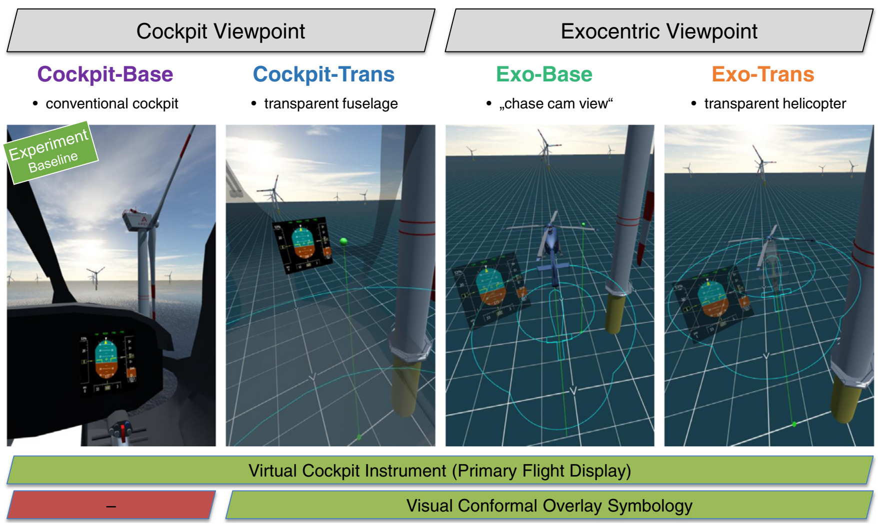

Fig. 8 Overview of the four developed 3-D perspective views. Screenshots are captured during different phases of the approach and hover maneuver next to a wind turbine tower. Visual conformal symbology shows the target position, the ownship position over ground, and the size of helicopter and safety margin.

5.2.1 *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, and 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).

5.2.2 *Apparatus*

Similar to the first study, the experiment took place in the XRSim and the Oculus Rift CV 1 was used as HWD. Again, we applied the command model of DLR's EC135 research helicopter with AFCS as flight simulation.[23] "Rate command, direction hold" mode was enabled 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, steady head-wind with gusts varying in strength and direction was simulated. 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. This uncoupled, highly augmented flight control system simplified the flying task. Nevertheless, the pilots still had to constantly monitor their relative motion and adapt their aircraft attitude to compensate for the fast-changing wind conditions.

5.2.3 *Experimental design*

The experiment compared the four developed display types using a within-subject design with counterbalanced conditions. The study comprised two separate tasks: a hover task close to an offshore wind turbine and a landing task on an offshore platform. Each task was flown twice with the same display condition. In total, each participant conducted 16 flights. All four flights with one display type were executed consecutively. The experiment procedure comprised briefing, training, testing phase, and debriefing. The total duration was around 3 h.

5.2.4 *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. 8, the desired hover point was positioned directly left of the wind turbine tower. The required 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.[14] The screenshots in Fig. 8 show different phases of this maneuver, from the final approach to the actual hover phase. The second task—the offshore platform landing—is not further discussed in this paper.

5.3 *Study Results*

The first part of the hover task was to find the desired hover location and acknowledge "on position." This was to measure how precise the pilots could estimate their spatial location with the tested 3-D perspective view. Figure 9 shows the distance between the actual target point and the position chosen by the pilots. A repeated-measures ANOVA revealed that the position deviation was significantly affected by the display variant, $F(3,21) = 8.553$, $p = 0.018$, and $\eta^2 = 0.429$. The boxplots show disadvantages for Cockpit-Base compared to the other display conditions. This effect was confirmed by Tukey *post hoc* tests ($p < 0.001$ for all three comparisons).

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 shown in Fig. 10, which shows top down views of all flight paths. The area covered while using the exocentric perspectives appears to be smaller than with the cockpit views. Moreover, the flight paths of the former are nearly centered around

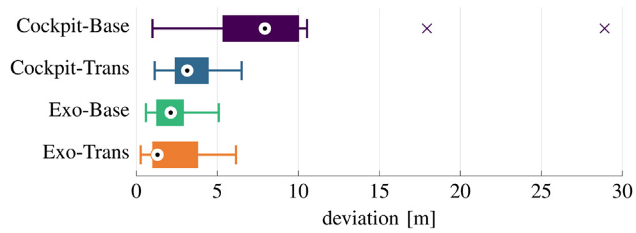

Fig. 9 Position deviation from desired hover point at the start of the hover maneuver. Boxplots show median (circle), 25th and 75th percentiles (bar), and outliers (x) with whisker length 1.5 IQR.

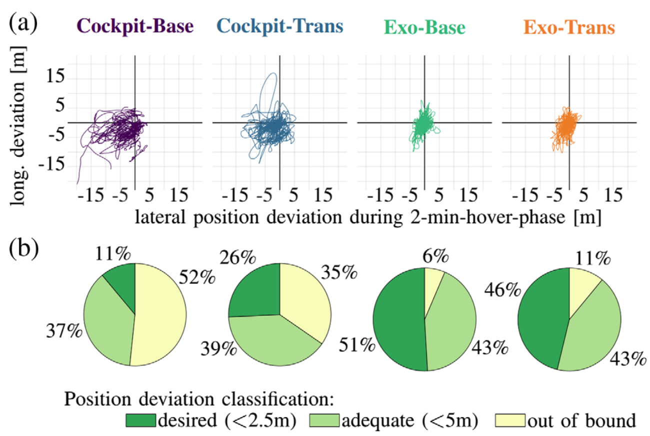

Fig. 10 Position deviation during the 2-min hover phase. (a) Top down view of all flight paths. (b) Pie charts showing percentages of the total hover time within three position accuracy classes.

Table 1 Post hoc comparison of the perspective views regarding hover duration in the "desired" zone.

Comparison			p	
Cockpit-base	–	Cockpit-trans	0.175	
Cockpit-base	–	Exo-base	<0.001	*
Cockpit-base	–	Exo-trans	<0.001	*
Cockpit-trans	–	Exo-base	0.003	*
Cockpit-trans	–	Exo-trans	0.024	*
Exo-base	–	Exo-trans	0.915	

*Indicate statistically significant differences.

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: deviations smaller than 2.5 m are categorized as "desired," differences up to 5 m correspond to "adequate." The pie charts in Fig. 10 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" and "adequate" limits around 90% of the total hover time. A repeated-measures ANOVA confirmed that the type of perspective view has a significant effect on the hover duration in the "desired" zone, $F(3,21) = 11.490$, $p < 0.001$, and $\eta^2 = 0.475$. As shown in Table 1, Tukey post hoc tests

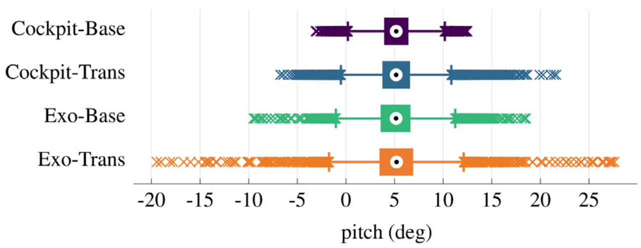

Fig. 11 Distribution of recorded pitch angles during the hover maneuver. Boxplots show median (circle), 25th and 75th percentiles (bar), and outliers (x) with whisker length 1.5 IQR.

revealed that both exocentric viewpoint variants performed significantly better than the cockpit views.

To evaluate the pilots' ability to judge and control helicopter attitude in the tested perspective views, the distributions of recorded pitch angles are shown in Fig. 11. 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 do not significantly differ. 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 nonconventional perspective views. The fact that the width of the boxes representing the middle 50% of the values varies less than 1 deg between the display conditions, indicates that the overall difference is relatively small. Fewer than 1% of the angles deviate more than 10 deg from the median in the nonconventional views.

Subjective feedback from a debriefing questionnaire and pilot comments confirm the objective findings. 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.

A comparison of the cockpit with the exocentric viewpoint in Fig. 12 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.

The visual conformal symbology was rated very positive for the exocentric perspective views. Both the safety margin circle and the green target balls were clearly found useful. In addition, 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. However, the visual conformal symbology appeared to have flaws in the cockpit view. For instance, the vertical green dropline was hardly usable in this display condition since the pilots had to tilt

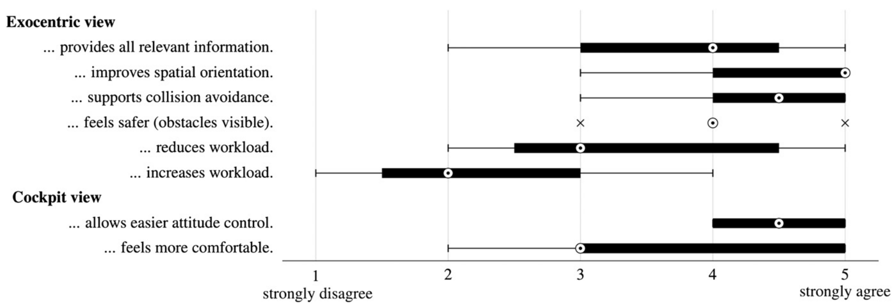

Fig. 12 Comparison of cockpit and exocentric view. Boxplots show median (circle), 25th and 75th percentiles (bar), and outliers (x) with whisker length 1.5 IQR.

their heads far down to see the line and the target dot under the aircraft.

The mean total scores of a 3-D SART questionnaire[45] were 83.75 for Cockpit-Base, 88.75 for Cockpit-Trans, 96.88 for Exocentric-Base, and 103.13 for Exocentric-Trans (averaged over the whole experiment). A significant effect of the display type on the SART total score was found by a repeated-measures ANOVA for the hover task, $F(3,21) = 4.805$, $p = 0.011$, and $\eta^2 = 0.159$. Tukey post hoc tests revealed that the scores of Cockpit-Base were significantly lower than the values obtained for Exocentric-Base ($p = 0.003$) and Exocentric-Trans ($p = 0.007$). All other comparisons were not significant.

5.4 *Study Discussion*

This study should investigate if the developed 3-D perspective views improve the pilots' perception of the environment, and if it is still possible to control the helicopter with such displays.

The experiment showed that the tested exocentric perspective views with visual conformal overlay have clear advantages over the conventional cockpit view presented on VR goggles. In the simulated hover scenario, pilots could find and hold the desired hover point more precisely. In addition, 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. As can be seen from Fig. 10(a), the pilots 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, toward 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. In addition, 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 a tendency that participants commanded higher maximum and lower minimum pitch angles with all three nonconventional view 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 such as 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 horizon 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.[14]

The 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.

Regarding the two research questions stated above, it can be concluded that—concerning this task—the pilots could better estimate and hold their position with the exocentric perspectives compared to the VR-based cockpit views. Nevertheless, the study showed that the pilots' ability to judge and control helicopter attitude should be further investigated. Moreover, the transparent cockpit perspective appears to have certain advantages over the nontransparent aircraft hull. However, the overlay symbology should be optimized for this view.

The description of this experiment is based on Ref. 16, where additional figures and descriptions can be found.

6 Conclusions and Future Directions

The paper introduces the VC, a concept of providing helicopter pilots with enhanced external vision information on an immersive HWD. It presents an advanced 3-D view of the surroundings, in which the pilots can naturally look around as they are used to when orienting themselves in good visual conditions without HWD. To explore the benefits of this solution, we built a development and simulation environment called XRSim and conducted two studies.

The experiments prove the potential of the VC. Especially the exocentric perspective views appear to have great capabilities to increase spatial awareness in confined area operations. Compared to the conventional cockpit view, the pilots' hover performance next to an obstacle was significantly improved and higher situation awareness was reported. Nevertheless, the work also revealed issues to be further investigated. For instance, the impact of the restricted

FOV through the VR goggles and the attitude control in exocentric views should be examined in more detail. In the mid-term, the step from testing pure display concepts to integrating the whole data acquisition system is planned. Moreover, other pieces of the concept such as interaction mechanisms may be implemented. Along with the conceptual development, the involved technologies must be further advanced in order to overcome the discussed current technical limitations.

It is essential to note that the presented experiments have been conducted in a pure VR setup. This was sufficient for the initial exploratory research on this topic. To ultimately assess the capabilities of the VC, we plan a comparison with the state-of-the-art AR and PMD solutions as well as flight tests. The potential of this concept, which is indicated by the first studies, gives reason to go these next steps.

In our opinion, the advantages of such a system make it a potential candidate to replace—in the long-term—PMDs and transparent HWDs in DVE scenarios. Initially, an immersive HWD could be used in a conventional cockpit as an add-on being applied in certain scenarios where it generates explicit benefits. VCIs could provide large display areas and later successively replace PMDs, which saves weight and space in the helicopter.[13] The VC may not be feasible for purely manually controlled aircraft but is applicable to future helicopters with modern autopilot systems and a high level of automation. With the VC in such a helicopter, an operation does not have to be conducted fully automated. Instead, the pilots can interactively take decisions based on their virtual out-the-window view and actively command the aircraft during the mission. As this paper shows, a number of challenges must be met to achieve this goal. Nevertheless, the pace of current technological evolution gives reason to predict that the required capabilities might be reachable in the future.

Acknowledgments

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