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Synthetic vision on a head-worn display supporting helicopter offshore operations

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ABSTRACT

Helicopters play an important role during construction and operation of offshore wind farms. Most of the time helicopter offshore operations are conducted over open water and often in degraded visual environment. Such scenarios provide very few usable visual cues for the crew to safely pilot the aircraft. For instance, no landmarks exist for navigation and orientation is hindered by weather phenomena that reduce visibility and obscure the horizon. To overcome this problem, we are developing an external vision system which uses a non-see-through, head-worn display (HWD) to show fused sensor and database information about the surroundings. This paper focuses on one aspect of our system: the computer-generated representation of relevant visual cues of the water surface. Our motivation is to develop a synthetic view of the surroundings that is superior to the real out-the-window view. The moving water surface does not provide fixed references for orientation and sometimes even produces wrong motion cues. Thus, we replace it by a more valuable, computer-generated clear view. Since pilots estimate wind direction and speed by checking the movement characteristics of the water surface, our synthetic display also integrates this information. This paper presents several options for a synthetic vision display supporting offshore operations. Further, it comprises results from simulator trials, where helicopter pilots performed final approaches and landings on an offshore platform supported by our display. The results will contribute to the advancement of our HWD-based virtual cockpit concept. Additionally, our findings may be relevant to conventional, head-down synthetic vision displays visualizing offshore environments.

Keywords: Virtual Cockpit, Synthetic Vision, Helicopter Offshore Operations, Helmet-Mounted Displays, Head-Worn Displays, Virtual Reality, Degraded Visual Environment, Human Machine Interface

1. INTRODUCTION

Helicopters serve as the most important means of transport for the offshore industries. Rotorcraft bring workers to oil rigs, ships, wind turbines and platforms located far from the shore. Further, helicopter operators offer offshore emergency medical services and support during the construction of new wind farms. In our previous work, we analyzed the challenges and problems faced by pilots operating in this domain.[1] Our results showed that helicopter offshore operations (HOFO) are highly demanding for crew and equipment. We also identified potential areas for improvement.

One major issue appeared to be the lack of usable outside visual cues. In contrast to onshore scenarios, only few fixed objects exist and the water surface provides fewer valuable cues than onshore terrain and vegetation. Further, the sea often induces adverse visual motion cues because of its own movement. These problems are often even aggravated by weather phenomena further degrading the view. We try to overcome this problem by enhancing the pilots' view with specific symbology on a head-worn display (HWD).

Since see-through HWDs come with a number of limitations, we use a non-see-through HWD. These displays are also known as virtual reality (VR) goggles. This gives us great flexibility in symbology design and avoids adverse influences of the reality (glare, adverse motion cues, brightness issues). The system shall fuse sensor and database information to generate a synthetic view of the offshore environment that is superior to the real out-the-window view. By developing such a computer-generated out-the-window view, several questions for research arise. One important aspect is the representation of the ground surface: the sea, in case of an offshore

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scenario. Thus, this paper examines the question how to best represent the ocean surface in a non-see-through HWD. Four variants will be compared by means of a simulator study.

The paper contents are structured in the following way: Section 2 gives a short introduction to related research on synthetic vision displays. Section 3 presents the display concept for the synthetic ocean surface representation. This is followed by Section 4 describing the simulator study we performed to evaluate the developed symbologies. The results of the experiment are illustrated in Section 5. Finally, Section 6 discusses these results and draws conclusions for future work on this topic.

2. RELATED WORK

The representation of the ground surface in synthetic and enhanced vision displays has been researched extensively in the past decades. However, the main focus has been placed on the illustration of onshore environments and mountainous terrain in particular. These works were often motivated by the goal to increase situational awareness so as to avoid controlled flight into terrain (CFIT) accidents.

Generally, one has to distinguish between terrain representations for see-through HWDs and symbologies for panel-mounted cockpit displays. 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 panel-mounted cockpit displays have no see-through requirements and can make use of full-color screens. This yields to greater flexibility and more options for symbology development.

Depending on the specific application, many variations from photo-realistic to abstract representations can be found in literature. Muensterer et al.[2] developed a terrain grid overlay for see-through HWDs. It highlights the contour lines of the terrain and depicts the grid itself in lower brightness. This is to avoid clutter and maintain the see-through capabilities of the display. Further, the grid can be interactively switched off up to a certain radius around the helicopter. A head-down terrain imagery is generated by Szoboszlay et al.[3,4] for their brownout symbology called BOSS. A combination of forward-looking infrared (FLIR) imagery with light detection and ranging (LiDAR) data is displayed in the background of their advanced landing symbology. The field of view (FOV) of such a sensor-based view can be enhanced by applying distributed aperture systems (DAS) like the Elbit Brightnite infrared (IR) camera system. This was developed to supply the pilots with imagery on the HWD even if they look to the side. Bolton et al.[5] researched into spatial awareness in non-see-through synthetic vision system (SVS). Their ground representations applied grids and differently textured terrain visualizations in various combinations. The variants including a grid superimposed onto various terrain representations were found best in terms of spatial awareness. Shelton et al.[6] tested an external vision system based on high-definition TV cameras. The imagery displayed on large flat-panel screens in the test aircraft should be used as an replacement for the natural out-the-window view. This is, for instance, interesting for supersonic aircraft designs with restricted cockpit window areas. Finally, many colorful synthetic vision displays are available for general aviation (GA).[7]

3. DISPLAY CONCEPT – SYNTHETIC OCEAN SURFACE REPRESENTATION

It is essential for a pilot to know where the wind is coming from and how strong it is. The wind strongly influences the performance and flight characteristics of the helicopter. If at all possible, landings are conducted with headwind. Landing with side-wind is only allowed in moderate wind conditions.

The shape of the sea surface allows experienced helicopter offshore pilots to estimate wind direction and speed. Under calm wind conditions, the water surface is flat and looks like a mirror. With increasing wind force the waves grow in size and change their moving characteristics. Further, foam crests and spray appear. At very high wind speed, clearly visible foam streaks move in wind direction of the rough sea surface. A well-known classification of wind speeds and the corresponding appearance of the sea is given by the Beaufort scale.[8] Despite its usefulness in terms of wind estimation, the sea surface does not only have positive characteristics for offshore pilots. As explained in the introduction, the moving ocean surface does not provide fixed references for orientation and sometimes even produces wrong motion cues.

This leads to two major goals for the development of our synthetic ocean surface representation. The symbology should provide:

1. fixed visual references for the pilots to better perceive their relative position and motion
2. information about wind direction and speed

3.1 Developed Synthetic Ocean Surface Representations

The developed symbologies are primarily intended for non-see-through displays. All display variants are computer-generated representations of the ocean surface. However, our goal is not to get the graphics as similar to a real sea surface as possible. Instead, we want to generate a virtual ocean surface that contains useful information for the pilots and thereby improves their ability to fly over open water.

Four symbologies were implemented. The first is called *Natural*. It 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 3d-meshes called *Elevated* to simple, flat planes with special grid structures (*Flat-Round*, *Flat-Peak*). All synthetic ocean surface representations have in common that they are static. This means that no moving waves are presented. The synthetic water surface is positioned at sea level, where the pilots would see the real ocean surface in good visibility without wearing the non-see-through HWD.

All representations show the wind force in discrete levels. Level 0 corresponds to calm wind conditions. Non-zero wind weaker than 10 knots is classified as level 1. Level 2 represents wind speeds between 10 and 25 knots. Stronger wind is assigned to level 3.

3.1.1 Natural

The *Natural* representation incorporates elements from real water but only to a certain degree. It does not aim to exactly reproduce all types of foam and spray that can be seen under rough sea conditions. As illustrated in Figure 1a, 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 pilots should, for instance, not erroneously observe a helicopter drift velocity just because the waves under them move.

3.1.2 Flat-Round

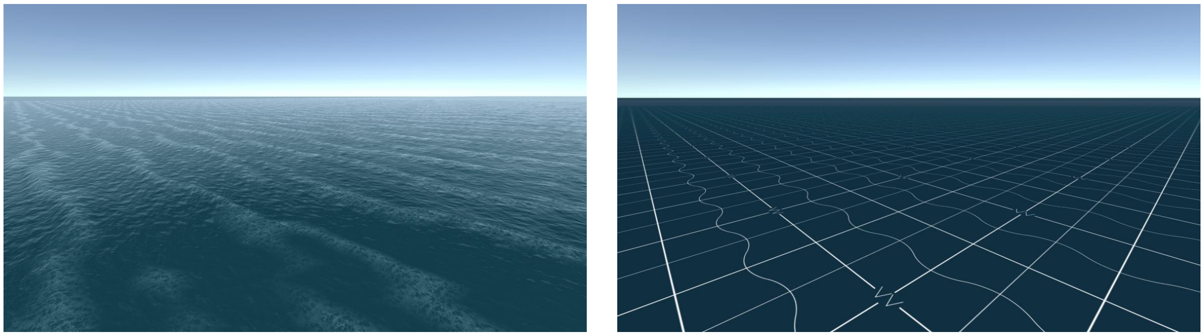
The *Flat-Round* display variant is a modified regular grid. The water surface is represented by a flat blue-colored surface. The grid lines are oriented parallel (and perpendicular) to the wind direction. As shown in Figure 1b, every second grid line perpendicular to the wind is replaced by a wavelike line. Arrowheads, located at the grid line intersections, are spread regularly over the surface. These point in the direction of the wind. The wind force is conveyed via the number of arrowheads. Additionally, the amplitude of the curvy line is increased and the wavelength is reduced for stronger winds. In calm wind conditions this display layout is a regular grid.

3.1.3 Flat-Peak

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 sinuous line are replaced by an undulated line with peaks on one side. The peaks indicate the wind direction like 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. A regular grid is displayed if the wind speed is zero. Figure 2a shows this display design for wind strength 2.

3.1.4 Elevated

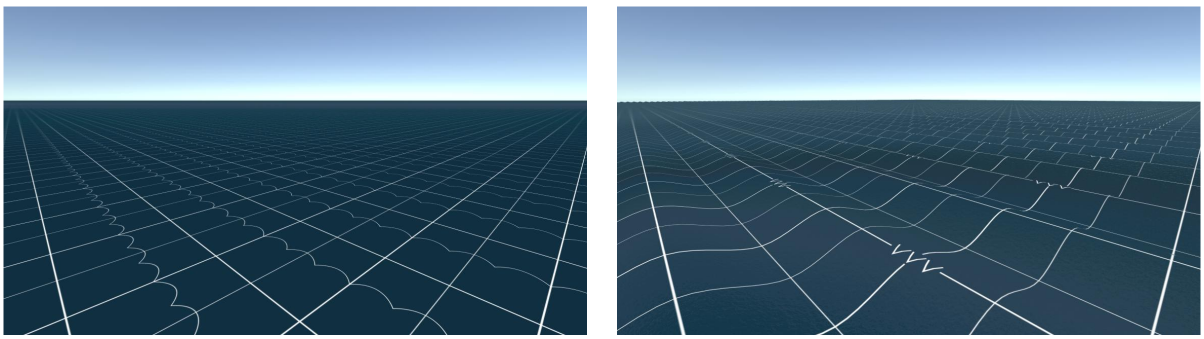
In contrast to the other layouts, the *Elevated* design is not flat. As can be seen in Figure 2b, the water surface is represented by a three-dimensional mesh with a uniform and steady wave structure. Moreover, the display comprises a regular grid oriented with the wind direction. The wave crest lines 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. Additionally, the height of the waves increases with the wind speed.



(a) The *Natural* symbology displaying a wind strength of level 3. The wave patterns are oriented perpendicular to the wind direction.

(b) The *Flat-Round* display in wind condition 2. The two arrowheads and the appearance of the wave line indicate wind direction and strength.

Figure 1 – Two of the developed ocean surface representations with wind coming from around 45° (from the right back to the left front in the images).



(a) The *Flat-Peak* representation indicating wind strength level 2. The peaks display wind strength and direction.

(b) The *Elevated* symbology under wind condition 3. High waves and three arrowheads indicate strong wind.

Figure 2 – Two of the developed ocean surface representations with wind coming from around 45° (from the right back to the left front in the images).

3.2 VR Cockpit Concept

The presented display formats are evaluated in our virtual cockpit simulator. Our virtual cockpit concept can be seen as a hybrid of two well-known types of displays used in degraded visual environment (DVE) operations: a see-through head-worn display and a conventional flat-panel cockpit display presenting synthetic/enhanced vision symbology. The result is a head-worn display that is opaque like a panel-mounted display. Thereby, advantages from both systems can be combined. On the one hand, the pilots can alter the display content by turning their heads. They can look around in the virtual environment like they are used to when orienting themselves in the real environment under good visual conditions. On the other hand, a non-see-through display offers more flexibility in symbology design. Furthermore, display glaring, brightness issues, and other undesired interferences between display and reality, which are known from see-through HWDs, are eliminated by design.

Figure 3 illustrates the concept of a virtual cockpit environment based on an HWD. The external view domain provides an artificial representation of the environment 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). Virtual instruments provide information such as flight parameters, navigation data, or aircraft systems status. However, our virtual instruments 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 re-designed layout making full use of new opportunities in VR. Thorough explanations can be found in earlier publications.[9,10]

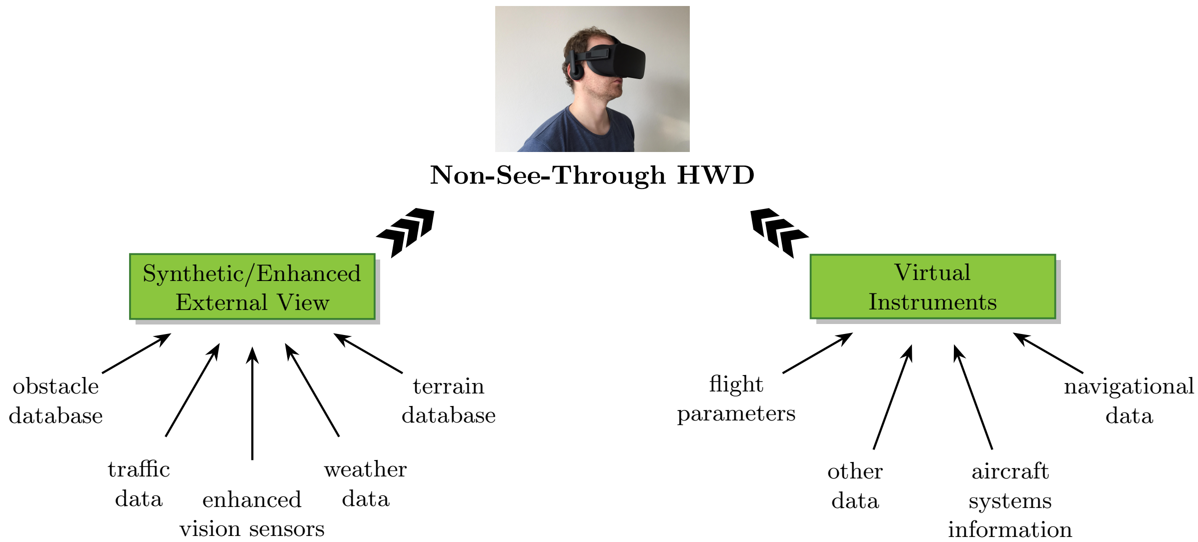


Figure 3 – Basic concept of our HWD-based virtual cockpit environment.

4. SIMULATOR STUDY – METHOD

The main goal of our simulator study was to get first feedback from pilots on the newly developed ocean surface representations. Besides collecting subjective feedback, the experiment compared how precise the pilots could judge the wind direction and their ground speed with this symbologies. Moreover, we wanted to get insights on how comfortable the pilots feel with the virtual reality glasses.

4.1 Participants

Nine male pilots with an average age of 36 (range from 25 to 60) participated in the study. Three had civil background while six subjects flew both military and civil aircraft. The mean flight hours of all subjects was 2236 h (min: 215 h, max: 6200 h). Regarding licenses, two owned a PPL, four a CPL, and three an ATPL. Four pilots had a mean experience of 18.5 h with head-mounted display. Six participants wore a VR headset like the Oculus Rift before (7.2 h on average).

4.2 Apparatus / Simulation Environment

Head-worn display The developed symbology was displayed on the Oculus Rift CV1 virtual reality headset. This VR headset mainly targets the consumer electronics and gaming market but is also well suited for display evaluation studies in our flight simulator. Table 1 provides an overview of its specifications. As shown in Figure 4, the system comprises a head-worn display and an IR camera. The latter tracks the HWD position by detecting several infrared LEDs embedded in the HWD unit. An inertial measurement unit (IMU) inside the goggles complements the head tracking mechanism. The Oculus Rift CV1 features two high resolution OLED displays one per eye to show a stereo-image with rather large FOV. The displays have a high refresh rate and low persistence. Data is transferred via USB 3.0 and HDMI cable connections.

Flight simulator The experiment took place in our Generic Experimental Cockpit (GECO), which is a fixed base, multi-purpose flight simulator. Its collimated outside vision system and the cockpit instrumentation were not used as the pilots wore virtual reality glasses with no see-through capability. The cockpit was equipped with professional, active force feedback flight controls. As flight simulation we used a custom-made model of our EC135 research helicopter with advanced flight control system (details below). Both the flight simulation and the display software run on the same workstation PC equipped with an NVIDIA GeForce GTX 1070 video card. The flight data transfer from the flight simulation module to the graphics generation module was realized via shared memory. Further, this data was sent via Ethernet to the data recording PC using the UDP protocol.

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.

Figure 4 – Oculus Rift CV1 tracking sensor and headset

(a) Generic Experimental Cockpit (GECO) with instructor station and pilot on the right seat.

(b) Pilot wearing the Oculus Rift VR headset during the experiment.

Figure 5 – The experimental cockpit setup during the simulation trials.

Flight control model To place the focus on the symbology evaluation, not on the flying task, we applied an advanced flight control system to our EC135 research helicopter model. With DLRs in-house development, the so-called command model, various command types and hold modes can be applied to all four control axes.[11] In this study we chose the following combination of modes: For the collective, *height hold* and *vertical velocity command* was active. This means that the pilot can directly command a vertical speed via the collective. If the collective remains unchanged, the helicopter stays at the current altitude. Contrary to a conventional collective, our collective returns and remains in the middle position (= no vertical rate), if it was not actively moved by the pilots. For the pedals, we applied the *turn coordination* mode implying that pedal inputs were not required at all. The lateral axis used *attitude command, attitude hold* to perform turns. For the longitudinal axis, *acceleration command* and *airspeed hold* was active. In summary, this means that the helicopter remained in straight and level flight if the flight controls were not touched in zero wind conditions. However, 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 groundspeed when turning into the wind.

4.3 Experimental Design & Procedure

A between-subject design was used. Besides the display type (*Natural*, *Flat-Round*, *Flat-Peak*, *Elevated*), wind speed and wind direction were independent variables in our experimental design. Levels of wind speed were 0 knots, 8 knots, 20 knots, and 35 knots. For the non-zero wind speeds, the wind direction could be 80° (right), 180° (tail), or 260° (left). Each pilot performed 16 flights, 4 per display condition. Each display type was tested with all 4 wind speeds. Also, each wind direction occurred once per display condition. All four flights with one display condition were conducted in a row. The order of these display blocks and the wind condition sequence was counterbalanced.

Each flight was split into two parts. The first segment was started in-flight, 500ft 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, 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°-turn into the wind and conduct a straight approach with constant deceleration and descent. Segment 2 was started in-flight (500ft above helipad elevation, 80 knots airspeed) with the landing pad located at 2 or 10 o'clock respectively.

During the whole experiment, no flight instruments except for the water symbology described in Section 3 were available. The pilots had an unobstructed view of the surroundings without any cockpit structure displayed around them in the virtual display. 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.

The experiment started with a briefing, followed by a short training for the pilots to acclimatize to the simulator and the head-worn display. The subsequent testing phase was conducted in two blocks of eight flights (approx. 50 min) separated by a 15 min break. During the final de-briefing, the participants provided subjective feedback on the display design and the virtual reality goggles by answering a custom-made questionnaire. The whole session lasted around three hours.

5. RESULTS OF THE SIMULATOR STUDY

Based on recorded simulator data, we conducted a thorough flight performance evaluation with the software MATLAB. Additionally, the results of several questionnaires and pilots' comments were summarized to illustrate the subjective feedback on the developed displays. The results are presented below.

5.1 Objective Performance Measures

The flight performance analysis in this paper focuses on the first segment: the wind direction and ground speed estimation task. Results from the subsequent approach task will be published in a follow-up publication. In total 108 flights (9 pilots x 4 displays x 3 wind conditions) were performed for this evaluation. The following results show how precise the participants could adapt their heading and estimate their ground speed based on the developed symbologies.

5.1.1 Wind direction accuracy

Pilots were asked to read the wind direction from the presented symbology and turn their helicopter precisely against the wind. Figure 6 depicts the deviations from this desired "headwind-heading" for each display variant. Every horizontal line in the plot represents one flight. The black squares illustrate the mean values while the whiskers correspond to the standard deviation.

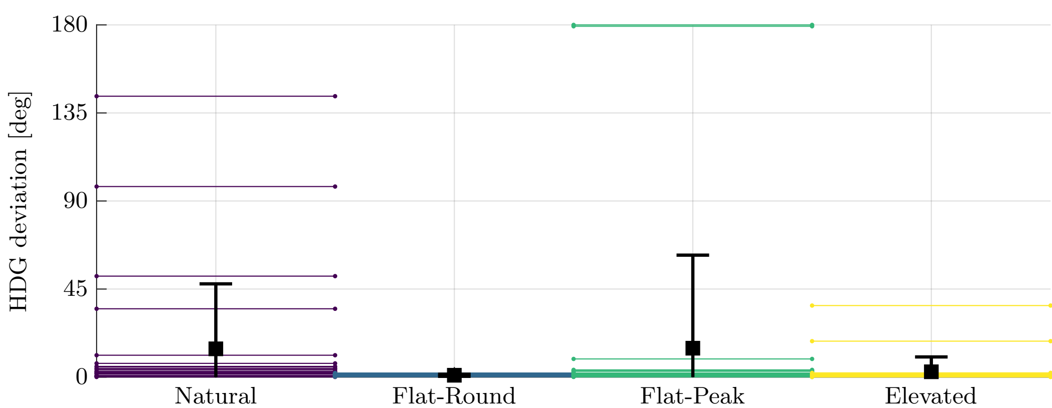


Figure 6 – Deviations from the desired "headwind-heading" under the 4 display conditions.

Figure 7 sums up our results by classifying the flights into four groups. If pilots deviated less than 2° from the heading given by the wind direction, the flights are categorized as "desired". Deviations up to 10° 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.

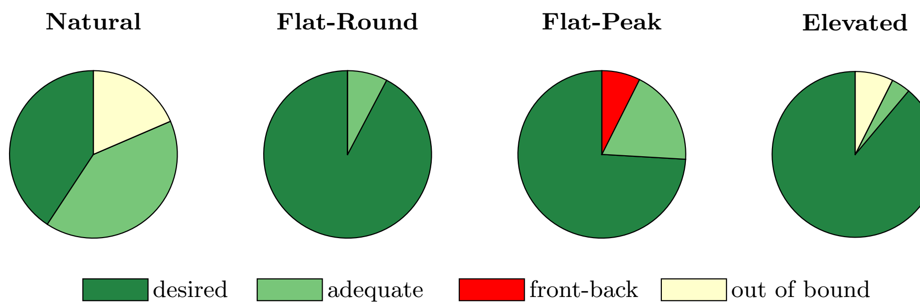


Figure 7 – Accuracy reached when turning against the wind based on the developed ocean surface representations. Results are grouped into four classes based on deviation from desired heading: "desired" ($< 2°$), "adequate"($< 10°$), "front-back" (opposite direction), and "out of bound".

Both graphs indicate that most results range between 0° and 10° being classified as "desired" or "adequate". Nevertheless, *Natural* caused fewer results in the "desired" range than the other display types. Additionally, more "out of bound" flights were observed under this condition. Interestingly, the *Flat-Peak* variant showed a number of front-back confusions meaning that the pilots flew in directly opposite direction with tailwind. *Flat-Round* and *Elevated* seem to be relatively equal as both generated more than 88 % "desired" flights. However, two runs with *Elevated* lay "out of bound".

5.1.2 Ground speed accuracy

Pilots' second task was to adjust the airspeed to maintain 60 knots ground speed when turned into the wind. The deviations from the wanted ground speed are plotted in Figure 8. Each flight is represented by one horizontal line in the plot. The black squares depict the mean values while the whiskers correspond to the standard deviation.

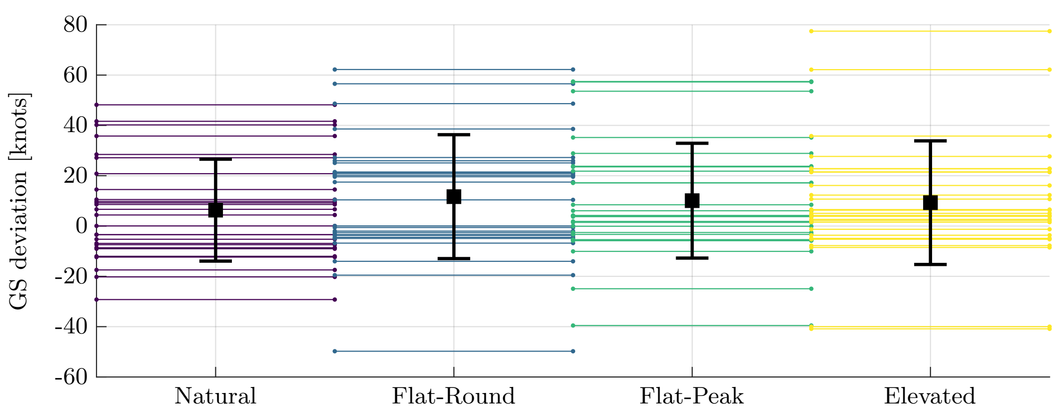


Figure 8 – Deviations from the desired ground speed for the developed display variants.

The results are categorized into 3 classes. If the pilots reached a ground speed closer than 5 knots to the desired speed of 60 knots, the flight is classified as "desired". Deviations smaller 15 knots are grouped into "adequate" while greater variations are assigned to category "out of bound".

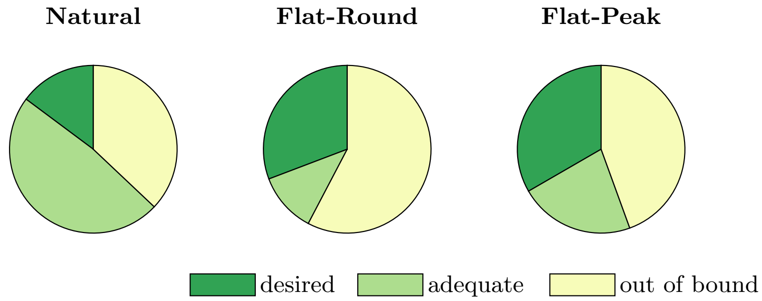


Figure 9 – Obtained ground speed accuracy categorized into four classes: "desired" (< 5 knots), "adequate"(< 15 knots), and "out of bound".

Both plots do not show clear differences between the four display variants. The obtained deviations from the wanted ground speed are spread between -50 knots (too slow) and 77 knots(too fast). The mean values indicate that on average pilots flew faster than desired irrespective of the display type. The fewest "desired" results were reached with the *Natural* ocean surface representation. However, the accumulated number of "desired" and "adequate" runs is slightly higher than with the other symbologies. In summary, the number of "out of bound" deviations is very high for every display layout (37-58 %).

5.2 Symbology Ratings

After each flight, participants rated if the presented symbology supported them during the past run. Figure 10 illustrates the accumulated results of this questionnaire. Pilots stated the degree of support they got from the presented symbology regarding estimation of wind direction and speed as well as performance of the flight task. For each aspect the *Natural* symbology was ranked lowest with most pilots disagreeing to the statements presented in the questionnaire. *Flat-Round* and *Elevated* were rated best regarding all three criteria. Their scores ranged around 4, which means "agree to the statement". *Flat-Peak* falls short of these symbologies especially in estimating the wind speed and performing the flight task.

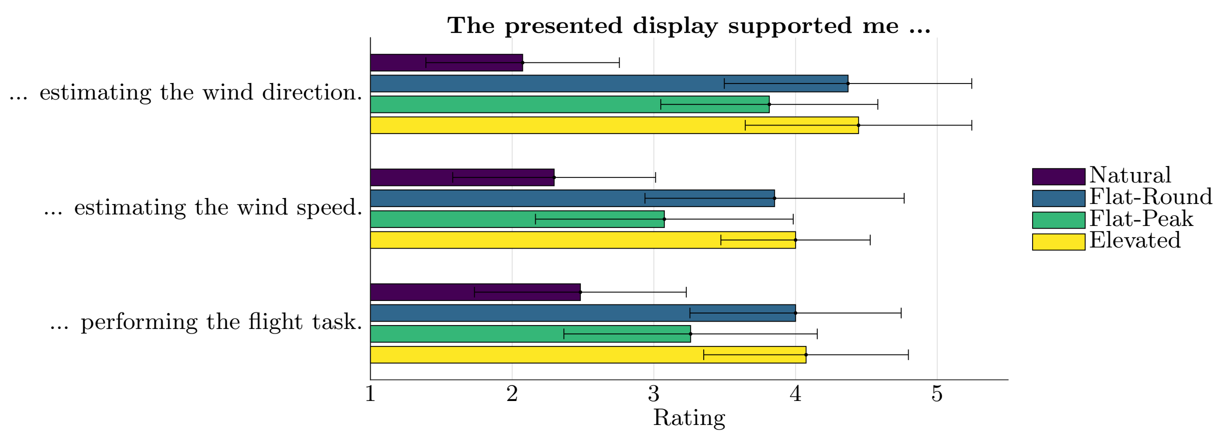


Figure 10 – Ratings (means, standard deviations) from the symbology questionnaire completed after each flight (1 = strongly disagree, 5 = strongly agree).

During the debriefing pilots were asked to give an overall rating of the developed ocean surface representations. Figure 11 illustrates that the *Elevated* design was favored receiving a mean rating of 4.7/5.0 ("very good"). *Natural* was on average rated 2.0/5.0, which corresponds to "poor". The other display variants range in between with advantages for *Flat-Round*. The large standard deviation for *Flat-Peak* indicates that its ratings diverged individually between pilots.

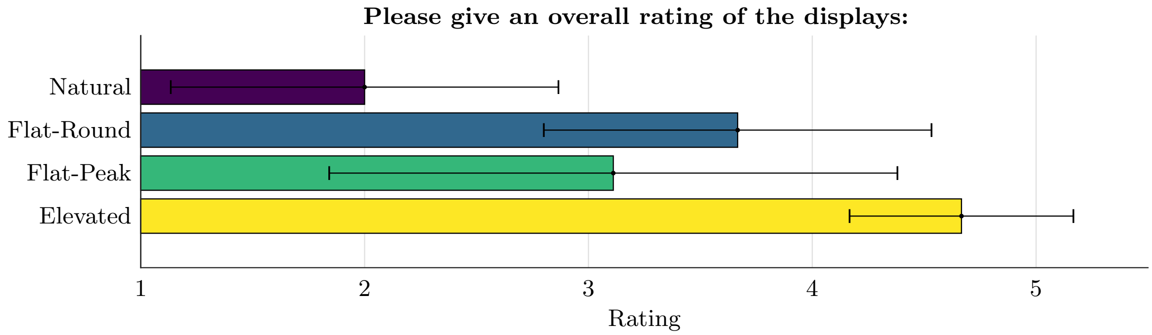


Figure 11 – Overall rating (means, standard deviations) of the developed ocean surface representations(1 = very poor, 5 = very good). This rating was part of the debriefing questionnaire.

In addition to the overall rating, different aspects of the display design were evaluated by means of the debriefing questionnaire. In general, Figure 12 shows the same tendencies as the overall ranking in Figure 11. Moreover, the final questionnaire revealed that all but one pilot agreed that "displaying wind direction and speed via a grid symbology is useful". Further, 7 of 9 participants stated that they prefer the wind indication arrows pointing downwind (as presented in the experiment) over arrows pointing in desired flight direction. Reasons were that they are used to this from weather reports and map displays. Further, they argued that one does not always fly against the wind.

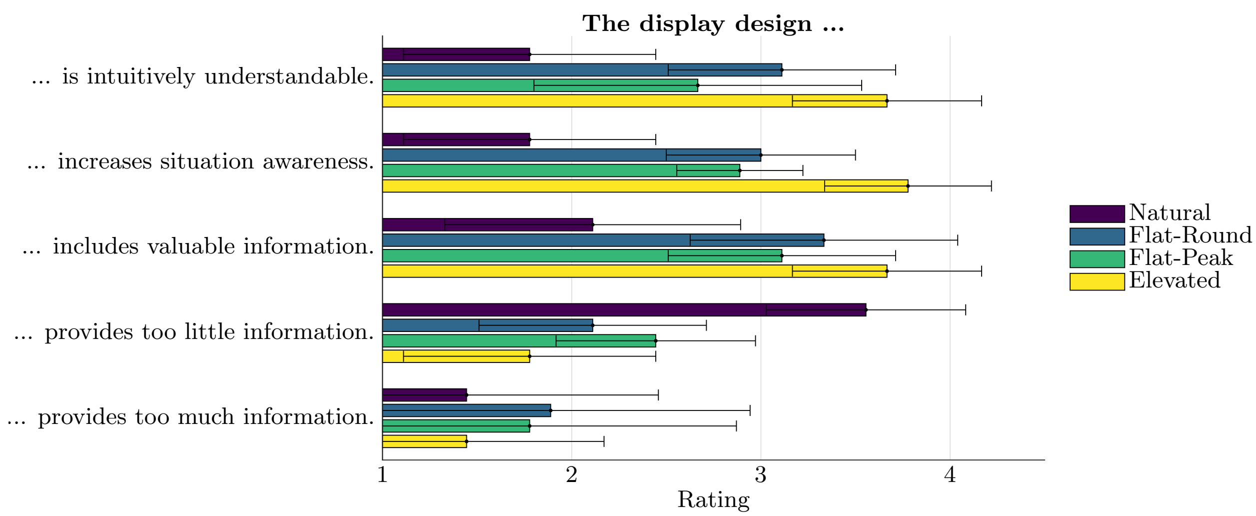


Figure 12 – Mean ratings and standard deviations of the display design rating (1 = strongly disagree, 4 = strongly agree). These questions were part of the debriefing questionnaire.

Finally, pilots' comments and suggestions were gathered throughout the experiment. All participants agreed that the ground speed was difficult to assess under all display conditions. Few pilots counted seconds required to pass a certain number of grid cells so as to better control their speed. Pilots admitted that their wind direction judgment often was not only based on the symbology but also highly affected by the perceived drift. Drift was clearer with the display variants containing grids. Thus, a feasible strategy was to turn until no drift was observed anymore. 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.

According to the pilots, the *Natural* symbology looked nice but included no valuable information. Both wind direction and speed were hard to assess. In particular, it was impossible to distinguish between head- and tailwind. Further, pilots commented that *Natural* is not realistic as the displayed waves did not move and the typical lines of white spume were not present. These are always parallel to the wind direction making them a valuable wind indication. One participant suggested that the curvy lines of *Flat-Round* and *Flat-Peak* would make more sense along the wind direction because they can be interpreted as equivalent to the white spume lines on the real ocean surface. As a result, these lines sometimes provided contradicting information for him. The majority of subjects agreed that this wave line in *Flat-Round* does not provide additional information as the wind speed is already clearly visible via the number of arrows. The wavy line in *Flat-Peak* was rated not intuitive by many participants as it could be interpreted as wind from both perpendicular directions. Regarding *Elevated*, the majority of pilots acknowledged that both wind speed and direction were intuitively visible via the height and orientation of the waves. A few preferred the arrows of *Flat-Round* in terms of wind strength display.

5.3 Head-Worn Display Rating

In summary, the Oculus Rift HWD was rated positively by the participants. The overall wearing comfort was reported to be "good": mean 2.2 on a scale from 1 (=very good) to 5 (=very poor). Also, the overall readability, contrast, and FOV were on average rated "good". No participant reported major problems regarding symptoms of virtual reality sickness. After around 2.5 h in the VR simulator, 4 of 9 pilots mentioned "weak" or "very weak" fatigue. Eyestrain, vertigo and headache was also reported rarely, but did not seem to be a major factor. Regarding visual issues, a few participants reported that blurred vision and image flickering occurred "rarely". One limitation of the HWD appeared to be that the peripheral vision was restricted. See-through HWDs may have a smaller FOV where symbology can be displayed, but they do not completely block the pilots' natural peripheral vision like the Oculus Rift does.

6. DISCUSSION, CONCLUSION AND FUTURE WORK

The results of the simulator study show that all three abstract display variants (*Flat-Round*, *Flat-Peak*, *Elevated*) are clearly favored over the *Natural* layout. This is true for the objective performance measures and the subjective ratings. With the abstract variants the pilots could turn into the wind very precisely whereas the results generated with *Natural* were less frequently within the desired range. This was expected as the grid provides a much better reference for that task than the wave patterns of *Natural*. In total, the abstract variants seem to perform quite equally. However, *Elevated* 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. Further, we cannot be sure that such misinterpretations would not also occur for other display variants if the sample size of the study was larger.

In general, we have to state that the pilots estimated the wind direction and speed not only based on the presented symbology. Instead they also based their decision on the drift of the helicopter. The grid made it easy to visually recognize even small drift velocities. Thus, pilots could judge the wind direction just by observing the behavior of the helicopter relative to the static ground representation (grid, waves), without interpreting the arrows of the symbology. In conclusion, the results might have been worse if the pilots had to rely on their interpretation of the wind direction symbols alone. This hypothesis is supported by a number of pilots stating during the flights that they would have turned downwind if visual perception of the side drift did not say something else. Hence, the number of front-back confusions was reduced by that, too. In conclusion, a grid even without additional wind indications will still be very helpful. Even the *Natural* symbology without grid helped the pilots since wave patterns were static. Both grid and static wave patterns serve as a fixed reference on ground which is usually not available over water. Thus, drift caused by wind from the side is clearly visible.

The subjective ratings support the flight performance results as the participants distinctly preferred the abstract variants. *Natural* is ranked worst in every aspect. 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." Even that symbology could be simplified by omitting the wavy lines.

The ground speed control task revealed that a precise estimation of the own speed only based on the developed symbology is not possible. On average, pilots were too fast. This might be explained with the fact that they wanted to compensate for the non-existent water movement of the static symbologies. In reality the impression of speed is amplified by the water moving in opposite direction under headwind conditions. This stimulus is removed in our static water representations. Following work has to further investigate, which cues contribute to the perception of the own speed in such a scenario. Then, the ground speed estimation could probably be improved by adding additional elements to our ocean surface representation. Moreover, specific training may enhance the pilots' speed perception with such static representations. Another factor that might have – at least partially – impaired the speed estimation is the missing peripheral vision through the VR goggles. The outer areas of the human vision play an important role in the perception of speed. However, the Oculus Rift provides only around 100° of horizontal FOV leaving about 50° on both sides occluded and black.

It is important to note that we can only assess the performance and acceptance of the implemented symbologies but make no comparison with reality. In particular, *Natural* should not be seen as a baseline representing the real sea surface. It has similarities but lacks important features. Hence, the abstract variants being better than *Natural* does not mean that they are better than the real ocean surface seen through the cockpit windows. Nevertheless, we can draw the conclusion that the wind direction estimation was such precise with the grid that the performance in visual flight can hardly be better.

In summary, the experiment proved that pilots can achieve good results with our three abstract ocean surface representations. Moreover, the head-worn display system was rated good by all participants. Despite the good results, we identified several shortcomings of the display designs and generated ideas for improvement. Thus, next steps will include the enhancement of the symbology based on pilot feedback and objective results of the study. Further, the ocean surface representation will be integrated with our existing, visual conformal symbology set for head-worn displays. In future versions, the ocean surface display system should also consider the specifics of real offshore wind as well as its measurement and forecast. Ever-changing wind directions and gusts, for instance, have to be low-pass filtered to ensure a smooth, non-distracting symbology. Otherwise the grid may alter its orientation continually. Finally, the usefulness of the developed symbologies should also be tested in head-down synthetic vision displays.

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