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Bringing a colored head-down display symbology heads up: Display fidelity review of a low-cost see-through HMD

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ABSTRACT

Within the U.S.-German project agreement on advanced technology for rotorcraft (PA–ATR) DLR conducts research on pilot aids for helicopter operations in DVE. For example, an HMD can provide visual cues to the pilot while flying eyes-out. With the HoloLens 2 as a low-cost HMD, the full-color waveguide display facilitates rapid prototyping of new color-coded symbology. To estimate the optical feasibility of the device, this paper presents findings on the see-through transmission of the combiner and a subjective rating of the color fidelity. The found issues can then be taken into account in the future design and development process of head-up display symbology.

Keywords: HMD, Head-Mounted Display, Head-Down Display, Augmented Reality, Mixed Reality, HoloLens, Color

1. INTRODUCTION

As part of the Project Agreement on Advanced Technology for Rotorcraft (PA–ATR) between the German Ministry of Defense and the US-American Department of Defense, the German Aerospace Center (DLR) conducts research on multimodal cueing to aid pilots during helicopter operations in Degraded Visual Environments (DVE). The objective is to reduce pilot workload and enhance situation awareness such that pilot errors are mitigated and to allow the execution of secondary tasks.

As DVE can drastically reduce the range of human vision, augmenting the out-the-window view with additional cues can improve the pilot's visual perception of the environment to reach the described objectives. In the past years, DLR's Institute of Flight Guidance used a military-grade see-through Helmet-Mounted Display (HMD) to test the developed symbology that aims to provide such visual cues. Even though it features a wide field of view and fast head tracking, use has decreased lately. Among others, reasons are

- the high effort for integration and commissioning in other simulators,
- increased paperwork required before use in DLR's research helicopter,
- the monochrome green display prevents the development and evaluation of color-coded symbology.

With these circumstances in mind, a new, inexpensive and more flexible see-through HMD was required to promote the research. Recent technological advancements in the field of virtual, augmented and mixed reality offer a wide range of devices that are eligible as an HMD for our described use case. One of those devices is the Microsoft HoloLens 2 that we found to be an acceptable replacement although display brightness, field of view and wearing comfort lag behind its military predecessor. However, with the full color display of the HoloLens it is now possible to display color-coded symbology that could previously only be shown head down (see Fig. 1 for current head-down display setup).

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Figure 1: A pilot sits inside DLR's helicopter simulator AVES using the Microsoft HoloLens 2 as a see-through HMD. A synthetic vision system in front, a topographical map, a Navigation Display and a Primary Flight Display to the left provide additional information.

In this paper, we review the color fidelity of the Microsoft HoloLens 2 with a selected set of colors. For that, a preceded literature research reveals possible colors that showed benefits when used on a HUD or an HMD. An overview of the features and the measures taken to integrate the HoloLens into DLR's helicopter simulator are also presented.

2. LITERATURE RESEARCH ON HMD COLOR CODING

Using colored symbology on flight displays has been researched for many decades, mostly with head down displays in mind. Due to the lack of see-through devices with full color display until a few years ago, there has not been the possibility or necessity to investigate the influence of color-coded head-up symbology. Although it is precisely the technical immaturity of these devices that would require a detailed investigation of the influence of different colors under varying light and viewing conditions. Only recently, there has been a growing number of publications addressing this topic.[1–6]

For instance, Havig et al.[7] presented subjects red, green and yellow symbology in increasing luminance contrasts on different natural background colors to find recognition thresholds. The results showed that especially yellow was detected incorrectly but also that yellow was confused with green.[7] Harding et al.[2] researched color contrast more exhaustively and mixed seven symbol colors with 14 different background colors over the entire contrast range. Besides normal color vision they also incorporated deuteranomalous color vision deficiency into their research and derived equations to calculate contrast from background luminance.[2]

Contrary to the examination of various symbology colors across a range of backgrounds, other researchers focus on specific colors.[1,3,4] Particularly the color blue is of interest because it becomes faint and colorless even in moderate daylight[4] but also because the sensitivity of the human eye to shorter wavelengths (i.e., blue with $450 - 495\,\mathrm{nm}$) is less during day operations than during night.[1] Hence, Foote et al.[1] suggest to use cyan instead of pure blue as the mixing with green adds brightness and can thus be better discriminated from other colors. Moffitt et al.[4] introduce an intermediate color *blue'* between blue and cyan that uses only 50% green light intensity as they found cyan to get confused with green. Blue' keeps the "blueness" instead while having improved luminance and detail vision, their tests revealed.[3] They conclude that the hybrid color blue' is a large improvement over regular blue during tasks where colored symbols had to be identified and text had to be read from a combiner.[4] However, blue'-colored symbology was still not as easy to identify as the rest of the evaluated colors, and text in blue' should be avoided as it becomes illegible even at moderate levels of daylight, they remark.[4]

3. INTEGRATION OF HOLOLENS INTO THE SIMULATOR

The Microsoft HoloLens 2 is an optical see-through Head-Mounted Display (HMD) from the consumer-electronics market. The display is full color and uses dual MEMS mirrors laser scanners with a 2D waveguide combiner.[8,9] Tracking the head position is done via an inside-out tracking system that analyzes the environment captured by four head-tracking cameras to create a internal map of the surroundings. An Inertial Measurement Unit (IMU) tracks the head motion and orientation.[10] Figure 2 depicts the HoloLens 2 and Table 1 lists its specifications. The horizontal field of view (FOV) of 43° is comparatively large compared to those of similar devices on the military market like the TopOwl by Thales (40°), the F-35 Gen III HMDS by Collins Aerospace (40°), or the Q-Sight by BAESystems (23°).[11,12]

Figure 2: The Microsoft HoloLens 2 can track the user's hands and eyes to enable a variety of interaction possibilities.

	Microsoft HoloLens 2
Display Technology	Laser projectors and waveguide
Field of View (FOV)	horizontal: 43°/ vertical: 29°
Head Tracking	Inside-out with four cameras, IMU
Eye Tracking	2 Infrared cameras
Other Sensors	1MP Time-of-Flight, RGB camera
Processing Unit	Qualcomm Snapdragon 850
Connections	USB-C, Wi-Fi, Bluetooth 5.0
Weight	566 g

Table 1: Technical specifications of the HoloLens 2.[13] The FOV is calculated from the 3:2 aspect ratio specified by Microsoft and a diagonal FOV of 52° confirmed by Alex Kipman[14] (lead developer of the HoloLens at Microsoft).

The software running on the HoloLens 2 was implemented using the game engine Unity.[15] To facilitate the development for the HoloLens as the end device we used the Mixed Reality Toolkit (MRTK) plugin.[16] For the drawing of display elements like the head-up Primary Flight Display or scene-linked symbology the Unity plugin "Shapes" is used.[17] For the exchange of flight and trajectory data a RabbitMQ server instance works as a message broker on one of our simulation PCs. To receive flight data from the RabbitMQ server via Wi-Fi on the HoloLens a basic message receiver was implemented using amqpnetlite, an AMQP1.0 library for .NET.[18]

When operating the HoloLens together with a fixed-distance dome projection like the Air Vehicle Simulator (AVES) at DLR, some problems arise. One issue is the mismatch between the perspective projection of the HoloLens and the fixed-distance projection of the simulator that causes a parallax error. To fix this, Walko[19] developed an algorithm to reproject the objects displayed on the HoloLens onto a (virtual) spherical surface. Then, this sphere needs to be aligned with the real dome surface of the simulator. The reprojection algorithm is integrated into the shaders of the "Shapes" drawing library such that the necessary computation is done on the graphical processing unit (GPU). The calibration process to align both spheres is performed by superimposing the edges of a wireframe box that both the HoloLens and the AVES can show (see Fig. 3).

Another issue is the erroneous detection of movement from the inside-out tracking: In a normal environment, the HoloLens detects movement through changing imagery of the head-tracking cameras. However, with a dome projection the HoloLens incorrectly interprets the movement of the outside vision as being moved although it did not move in the simulator frame of reference. To encounter this we use Spatial Anchors – a HoloLens built-in feature.[20] Spatial anchors stabilize holograms like the aforementioned virtual projection sphere by avoiding a position correction from a refined understanding of the detected environment. It is also possible to store and load these anchors between application sessions to prevent having to re-calibrate after an application restart.

Figure 3: A wireframe box is used to calibrate the HoloLens view with the dome projection of the AVES helicopter simulator. In red the wireframe as it would be rendered on the HoloLens is shown. The white equivalent is part of the dome projection. The octahedron at the far right of the image represents the simulator's design eye point position. Here, an uncalibrated state is shown for demonstration purposes.

4. CONDUCTED TESTS AND DISCUSSION

This section describes different tests we made to evaluate the optical feasibility of the HoloLens 2 as a see-through HMD. Therefore, we measured the see-through transmission and tested the color fidelity of the display. The findings are discussed based on the literature research.

4.1 See-through transmission

According to Rash et al., one key criteria when describing the optical system's performance of an HMD is the transmission of light through the combiner.[11] A higher see-through transmission results in a better visibility of the outside world but comes at the cost that the symbology needs to be brighter in order to be seen during daylight.

We measured the see-through transmission of the HoloLens 2 with an LS-100 luminance meter from Minolta. We held the luminance meter against a bright diffusive light source with a luminance of about $1905\,\mathrm{cd/m^2}$. Putting the waveguide combiner of the HoloLens 2 between the meter and the light source, repeated measurements resulted in transmission rates between $33\,\%$ and $35\,\%$. Comparing this result with the transmission of other HMDs' combiners reveals that the value for the HoloLens 2 is rather low: BAESystems' Q-Sight has a see-through transmission of $> 50\,\%$, for the LCD29 HMD by Trivisio a value of $70\,\%$ is given, and Elbit Systems offers the Variable Transmittance Visor (VTV) with a transmission that can range from $15\,\%$ up to $85\,\%$.[11,21,22]

4.2 Color fidelity

When trying to benefit from color-coding symbology, it is important that there is no confusion in the colors used. A misinterpretation of the displayed content can lead to wrong actions by the pilot causing severe consequences. Especially for see-through HMDs the use of color can be a delicate task as the preceding literature research showed.

In the case of the HoloLens 2, we selected a set of colors – listed in Tab. 2 – to investigate the color fidelity of the display. Therefore, the author subjectively evaluated the behavior of the different colors against a well-lit white wall. The colors were either shown as a rectangle filling the entire FOV of the HoloLens or as a colored Primary Flight Display (PFD). Fig. 4 shows photos taken through the combiner of the HoloLens while conducting the test with different PFD colors.

Looking through the HoloLens against the white wall, the colors were stable and appeared in the intended color for the most part. The display brightness (that is adjustable at the cost of battery life) is at an acceptable

Table 2: To test the color fidelity of the HoloLens 2, we selected a set of nine colors. Their names and RGB values are listed below.

Color name	RGB values
red	(255, 0, 0)
green	(0, 255, 0)
blue	(0, 0, 255)
magenta	(255, 0, 255)
yellow	(255, 255, 0)
cyan	(0, 255, 255)
pink	(255, 0, 128)
orange	(255, 128, 0)
blue'	(0, 128, 255)

level in an environment with controlled lighting (like the testing environment or inside AVES) but symbology becomes barely readable when viewed against even moderate daylight. This holds independent of display color.

Adjusting the fit of the HoloLens unveils a change of color across the eye box (i.e. the volume in space where the viewer's eye must be placed[11]). Particularly the up and down direction is prone to a color shift that was first noticed with a cyan-colored symbology: At the upper end of the eye box cyan appears like a deep blue and towards the lower end a shift towards green or even orange is visible. These blue shifts at the upper and red shifts at the lower end of the eye box could be detected for all tested colors. Even though the effect has been perceived as less severe for the monochromatic colors (red, green and blue) with blue being most stable but also least readable as it is inherently too dark.

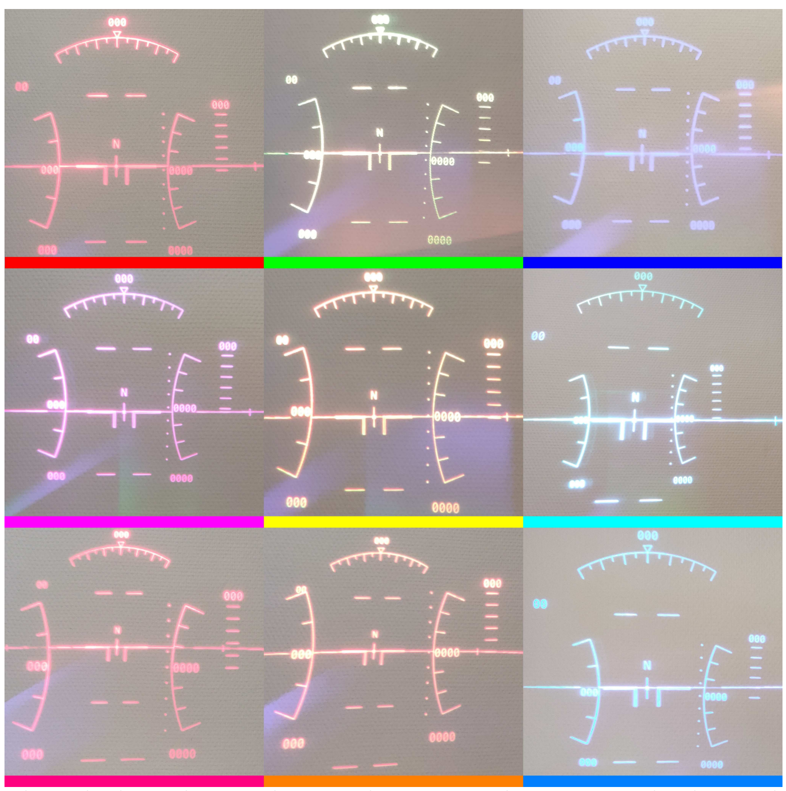

Figure 4: Photos taken through the HoloLens showing the PFD in the nine tested colors. The bar below each photo shows the intended color. It should be noted that this depiction is not an adequate representation of what is perceived with the human eye.

From the tested secondary colors, the ones that had half intensity in a second channel (pink, orange and blue') were perceived as more stable than the three colors with full intensity on two channels (magenta, yellow and cyan). In particular the blue alternative blue' appeared to shift only very slightly while being much brighter and hence better readable than blue. One reason might be the worse perception of wavelengths in the blue spectrum during daylight conditions. For orange, only a minor shift to yellow at the upper area of the eye box could be detected but a shift at the lower end was not perceived. It should also be noted that in the left and right direction shifts were not noticable due to the tighter fit of the HMD.

5. CONCLUSION AND OUTLOOK

5.1 Summary

The paper introduced the use of the Microsoft HoloLens 2 as a see-through HMD to conduct research in the field of multimodal cueing for helicopter pilots during flights in DVE. In order to translate our existing head-down symbology onto the HoloLens we had to adapt it to compensate for the shortcomings of such a low-cost device. The focus of this paper is to evaluate two important parameters of the optical architecture of the HoloLens to find these shortcomings. In a first step, we measured the see-through transmission of the waveguide combiner with a result between $33 - 35\,\%$. Compared to other HMDs, we found this to be a relatively low transmission rate. Second, to investigate the color fidelity of the HoloLens we rated the stability and readability of nine colors. The color set was selected based on a literature research on HMD color-coding: Besides the three basic colors red, green and blue, six secondary colors magenta, yellow, cyan, pink, orange and blue' were part of our set. Although the colors appeared stable when the HMD had the correct fit a slipping lead to the colors no longer being perceived as intended. Moving the device towards the nose (i.e. putting the eye in the upper area of the eye box) had the effect of colors to shift to blue. Seeing the colored symbology from the lower end of the eye box resulted in a color shift to red. This effect was stronger for the mixed colors than for pure red, green and blue.

5.2 Conclusion

The Microsoft HoloLens 2 is a low-cost enterprise see-through HMD with training and virtual product visualization as the intended field of application. Despite all the shortcomings that become apparent when operating outside of these application areas (like a flight simulator in our case) the HoloLens is a flexible solution for rapid prototyping and testing of new head-mounted display symbology inside a fixed-base flight simulator. However, for real flight tests a military-grade HMD with higher transmission of the visor, larger FOV, and a more powerful image generator – for symbology to be seen against bright daylight – should still be used.

5.3 Outlook

For our future work at DLR on developing and testing HMD symbology the HoloLens currently is the best alternative to a military see-through HMD. The color display allows us to evaluate the color-coding of different symbology parts (Primary Flight Display, scene-linked symbology, threat visualization) in the near future. Furthermore, the advanced possibilities for interaction the HoloLens offers – like eye tracking, gesture recognition and spatial sound – leave room for further research on multimodal interactivity with the helicopter system or to fulfill secondary tasks more accurately and quickly. However, the findings should be taken with care as the HoloLens is not meant for highly challenging application areas like aviation and the limitations of the device can have impact on the gained results.

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