AR in VR: Simulating augmented reality glass for image fusion

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Abstract

Developing an augmented reality (AR) system involves a multitude of interconnected algorithms such as image fusion, camera synchronization and calibration, and brightness control, each having diverse parameters. This abundance of features, while beneficial in nature for its applicability to different tasks, is detrimental to developers as they try to navigate different combinations and pick the most suitable configuration for their application. Additionally, the temporally inconsistent nature of the real world hinders the development of reproducible and reliable testing methods for AR systems. To help address these issues, we develop and test a virtual reality (VR) environment [1] that allows the simulation of variable AR configurations for image fusion. In this work, we improve our system with a more realistic AR glass model adhering to physical light and glass properties. Our implementation combines the incoming real-world background light and the AR projector light at the level of the AR glass.

Keywords: *augmented reality, virtual reality, augmented vision, simulation, optics*

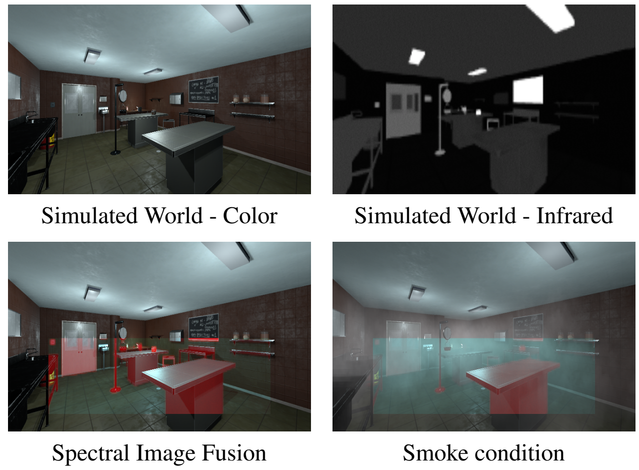


Figure 1. *AR in VR infrared vision simulation [1] (red and cyan on the AR display correspond to warm and cold areas, respectively)*

Introduction

The recent advances in augmented reality (AR) motivated a wide range of wearable headsets such as Microsoft HoloLens and Epson Moverio as well as numerous applications in industry and entertainment. In particular, augmented vision is a special AR application that enhances user's sight through an optical see-through head mounted display (OST HMD) and is used for vision correction [2] and night vision [3]. Under the framework of augmented vision, visible and thermal image fusion [4,5] can help firefighters navigate through low visibility environments caused by smoke or darkness [6, 7].

Firefighters typically deal with life-threatening situations, so it is vital to ensure the reliability and performance of their AR system. However, conducting controlled comparative studies can be challenging due to reproducibility issues that arise from the ever-changing real world and the risk of using untested methods in a fire situation. In prior work [1], we create an AR simulation of image fusion in a virtual reality (VR) environment to circumvent these difficulties. Using Unity3D [8] and Oculus Rift [9], we simulate a thermal camera. We then implement and compare multiple image fusion methods under varying visibility conditions. We also build a simple AR display simulation to illustrate what a user would see on a real OST HMD. Fig. 1 show the simulated color and infrared images as well as an image fusion method projected on an AR display in normal and smoke-heavy visibility conditions.

In this work, we improve the user's immersion by creating a more physically accurate AR display adhering to physical light and glass properties. The AR display consists of a semi-transparent combiner glass that blends the real-world background light with the AR projector light. We first explain how the combiner mixes the lights with a simple implementation. Then we will study the interactions between the glass and the incoming lights and the system's optical characteristics. We implement these properties and present a configurable AR display that supports realistic light behavior.

Code can be found at https://infoscience.epfl.ch/record/255390/files/

Related Work

Our main objective is simulating AR systems in VR. We study how previous simulations in VR were used to conduct experiments and system evaluations.

Lee et al. [10] replicates an OST HMD AR study. They rebuild the scenario in a virtual world and conduct the same evaluations. Even though their model is not completely faithful to the original experiments, they are still able to obtain comparable results. However, in a future work [11], they show that small variations in latencies affects the results obtained. These experiments show that the virtual world should try to replicate the real world as close as possible, hence our focus on having physically-based light mixing at the AR display level.

Another study [12] researches the effects of outdoor background texture and illumination over the legibility of virtual textual elements in AR. The authors obtain reliable conclusions for low light environments (dawn, dusk, indoor) but are not able to replicate the same experiments for outdoor illumination. This is because artificial light sources cannot replicate outdoor brightness, and the differences between background and display lights is not perceived. In our implementation, the configurable AR display mixes different brightness levels from both sources in XYZ space to reduce the effects of this problem.

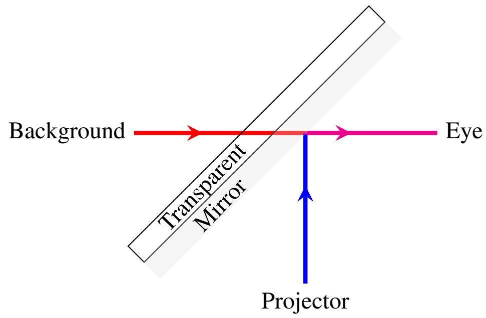


Figure 2. *Light blending through a semi-transparent combiner*

Ventura et al. [13] simulate different properties of the AR display. They study the effects of field of view and sensor reliability on X-ray vision in an AR simulation. This work is parallel to ours as it allows modifying physical properties of the AR system and study them in a virtual environment.

Finally, VisMerge [14] proposes an AR simulation to compare fusion methods. However, they display the fusion on top of the users whole field of view, without having an intermediary AR display. In our work, we develop an AR glass with configurable properties to display the image fusion.

Combiner

In an HMD, the display light I_d is additively blended with the background light I_i. In order to account for the differences in brightness between the background and display lights, the mixing is done in the XYZ color space by fixing a different maximum luminance to the transformation from RGB to XYZ for each light source. The output light I_o is thus computed as

$$I_o = I_i + I_d \tag{1}$$

We initially implement light blending following Eq. 1 in Unity Shaders using a linear space and render them in VR using a gamma correction. However, this method does not represent the physical properties of the AR display. In a real AR system, the combiner is a semi-transparent glass that reflects the display light (virtual image) to the eye, while letting the background light partially pass through it, thus achieving light blending. The background light is refracted when it passes through the combiner material, while the display light is reflected on the opposite side. In the following sections, we discuss these interactions, the optical distortions that modify the light's structure and propagation, and our corresponding implementations.

Background Light

The background light hits the transparent side of the glass, it travels from air into the AR display and back to air before reaching the user. The light, passing through a different material, is refracted and loses part of its power. Additionally, different wavelengths are refracted at different angles and light is dispersed when it exits the AR display. In this section, we explore and implement these properties at the level of combiner.

Refraction

Refraction is the change in direction of light propagation or any other wave when it changes media because its speed differs in each material. Usually, if a ray slows down while passing through a new medium, its direction will bend towards the normal of the boundary between the two media. The angle of bending depends on the indices of refraction of the two media and is described by Snell's Law. It relates the angles of incidence θ_1 and refraction θ_2 to the indices n_1 and n_2 of both media by:

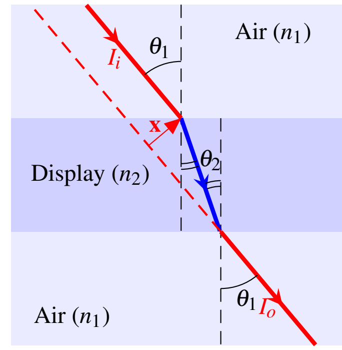


Figure 3. *Backward refraction through an AR Display*

$$\frac{n_1}{n_2} = \frac{\sin(\theta_2)}{\sin(\theta_1)} \tag{2}$$

In our case, the background light passes through the AR display, from a medium with a lower index of refraction n_1 to a higher n_2 and then back to the lower n_1 medium.

For rendering, we are only interested in the rays hitting the eye (camera), as the others will not be seen. We rebuild the refracted ray following a backward path as shown in Fig. 3. In order to satisfy Snell's Law on both sides of the display surface, we must have the incoming ray I_i and the outgoing ray I_o at the same angle from the display surface, so they must be parallel to each other. I_o is a translation of I_i by a vector $\mathbf{x}$. Assuming the display has a thickness t, the light travels for a distance of

$$d = \frac{t}{\cos(\theta_2)} \tag{3}$$

Then the length of $\mathbf{x}$ is

$$|\mathbf{x}| = d\sin(\theta_1 - \theta_2) = \frac{t}{\cos(\theta_2)}\sin(\theta_1 - \theta_2) \tag{4}$$

The shift only depends on the thickness of the display and the incident angle since θ_2 can be found from θ_1 using Snell's Law. In the backward pass, we shift in the reverse direction of $\mathbf{x}$.

Figure 4. *Refraction example with* $n = 1.5$

In Unity, for every vertex on the AR glass, we find the corresponding background pixel by shifting its position based on the angle θ_1 between the AR screen and the camera. In Fig. 4 we can see the refraction effect with $n = 1.5$. The effects can be best perceived at the edges of the door.

Transmittance

When light passes through the AR glass, only a fraction of its power is transmitted. The rest is either reflected or scattered. The surface transmittance of a material quantifies its effectiveness in transmitting the energy of the incident light through its surface.

Additionally, light loses part of its energy due to absorption. This is the internal transmittance of the material. For both transmittance models, the incident I_i and transmitted light I_t are related by

$$I_t = t_D I_i \tag{5}$$

In our implementation, we model this by including a configurable variable to tune the transmittance of the AR display. Fig. 5 shows the light partially passing through the AR display. Prior work [15] shows that t_D is typically close to 0.5.

Figure 5. *Transmittance example with $t_D = 0.5$*

Chromatic Aberration

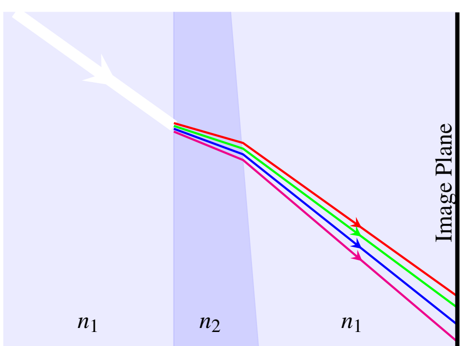


Figure 6. *Dispersion of white light passing through a slanted material*

In the previous section, we assume a single refraction index. However, the refractive index varies with the wavelength of the light. This causes different wavelengths to disperse when exiting the surface. This effect can be seen in prisms, for example. Since each wavelength, i.e. color, is slightly shifted from the others, the colors of the incoming light fails to focus on the same convergence point. This chromatic aberration is manifested as color fringes along the boundaries of the image, as illustrated in Fig. 6.

In Unity, colors are manipulated in an RGB space. In order to replicate chromatic aberration, we add an amount of dispersion per color in the RGB color space. This allows us to tune **RedCyan**, **GreenMagenta** and **BlueYellow** shifts in the image resulting in the aberrations shown in Fig. 7.

Red-Cyan Dispersion

Green-Magenta Dispersion

Blue-Yellow Dispersion

Dispersion in all three channels

Figure 7. *Dispersion examples*

Projector Light

The display light, emitted by the AR projector, reflects on the mirror surface of the semi-transparent combiner and travels towards the user's eyes. In addition, the light partially traverses through the non-perfect mirror surface and is internally reflected backwards creating ghost images. In this section, we discuss the interactions between the projector light and the AR display. In the following, the transparency of the AR display is turned off to only show the display light.

Reflection

Reflection is the change in direction of a wave at an interface between two different media so that it returns into the medium from which it originated. Light can be reflected in two ways. A specular reflection behaves like a mirror returning the wave at a reflected angle equal to its incident angle. A diffuse reflection happens when the light bounces off in all directions due to microscopic irregularities inside and on the surface of a material. In our case, we suppose the AR display surface is a mirror and most of the light is directly reflected. However, even in that case, only a part of the light is reflected as some of it still is absorbed, transmitted, or diffused. We control this amount of light using a reflectivity r_D, variable which decides the amount of light I_r reflected from the projector display light I_d such as:

$$I_r = r_D I_d \tag{6}$$

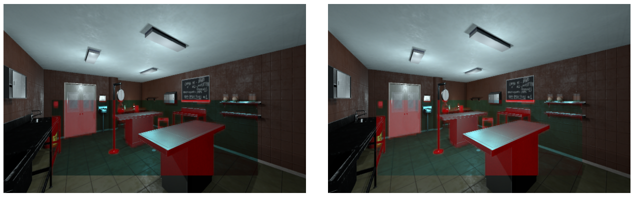
With transmittance and reflectivity, Eq. 1 becomes:

$$I_o = I_t + I_r = t_D I_i + r_D I_d \tag{7}$$

The effects of varying the reflection value is shown in Fig. 8. Higher values of r_D allow for more light to be reflected and results in a brighter display.

Ghost Images

As stated in the previous section, the projector light I_d is partially reflected as I_r. The remaining fraction of light $I_m = (1 - r_D)I_d$ travels through the glass. On the other side of the AR display, I_m is internally reflected into I_{m_r}, and refracted on the other side as I_g, which is a parallel ray to the originally reflected ray I_r hitting the eye. Fig.9 illustrates this process.



$r_D = 0.5$ $r_D = 1$

Figure 8. *Reflection example*

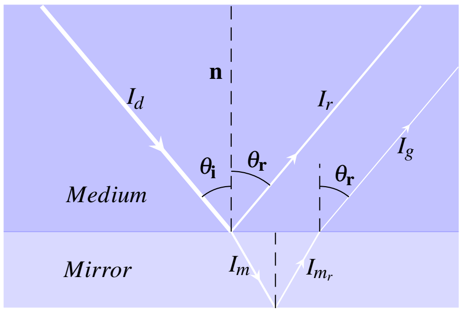


Figure 9. *Light path after reflection*

I_r and I_g are parallel reflections of the projector light I_d. Subsequently, the user perceives two slightly shifted images. In order to model this ghost effect, we measure the shift in the image as well as its intensity. Then, we sample shifted and dimmed pixels from the fused image and add them to the original result. Fig. 10 shows the example of a dim ghost image appearing slightly to the left of the original image. The effect is most noticeable at the closest side of the table as well as at the sink in the background.

Figure 10. *Ghost image example*

In this process, the light loses energy at three stages before returning following I_g. We can already measure the first one as $(1 - r_D)$. For the internal reflection and following refraction, we assume the light loses energy by a combined factor r_G which encodes both losses. In the end, we compute the intensity of the ghost image I_g from the original display light I_d as:

$$I_g = r_G(1 - r_D)I_d \tag{8}$$

As such, we update Eq. 7 to accommodate this new light, and it becomes:

$$I_o = I_t + I_r = t_D I_i + r_D I_d + r_G(1 - r_D)I_d \tag{9}$$

Discussion

We started with the goal of developing a realistic augmented reality display that combines real-world background and AR projected information. Our model was built in Unity using their shader language. We studied the light pass from the background and the projector to the user's eyes.

The background light goes through the display, gets refracted and partially absorbed, possibly also dispersed. We explored how the light progresses through these stages and implemented a physically based rendering of these phenomena.

Similarly, we followed the path of the projector light reflecting on the mirror and partially passing through and bouncing back to form ghost images.

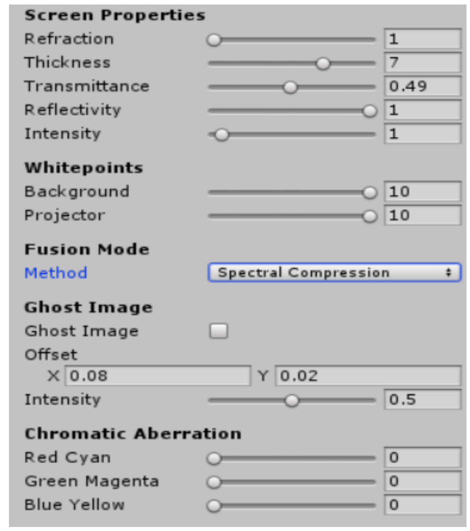


Figure 11. *Unity UI for AR Glass*

Studying the physical properties of the light helped us gain an understanding of how to better simulate them. Even if the simulation is not completely analogous to the real light trajectories, we were still able to approximate it using Unity's shaders and produce similar behaviors such as chromatic aberrations, energy loss and ghost images.

In order to allow a developer to fine-tune the AR display simulation, we also created an UI to help them decide how to configure the display. In Fig. 11, we show the tunable parameters for refraction, transmittance, reflectivity, ghost images and chromatic aberrations among others. This helps the users simulate different phenomena that they find interesting to test.

Conclusion

Our glass model allows simulating different light properties that affect the semi-transparent combiner. The AR display itself is very flexible and can be easily modified to account for different models or focus on singling out glass characteristics. The current model still lacks the implementation of other effects such as vignetting, as some projectors focus the light on the center of display, resulting in a vignetting effect on the borders. Another effect that could be studied is the border reflections, as some AR devices have a higher thickness along the edges of the display. It might either block the vision around that area, or create mirror reflections coming from different background locations.

Acknowledgments

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