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# BEYOND REALITY: Head-Mounted Displays for Mobile Systems Researchers

Head-Mounted Displays (HMDs) have finally reached the point where they can comfortably and affordably transport people to virtual worlds or transform their physical reality by feeding timely information straight to their eyes. However, the technology behind HMDs is still not fully mature. There are plenty of open challenges in wireless networking, cloud computing, security, and privacy, as well as opportunities to create novel applications.

Photo, istockphoto.com

Immersion, the illusion of being physically present in a world that does not physically exist, has long been an aspiration of many scientists, engineers, designers, and artists. For more than 50 years, several head-mounted displays have been designed, prototyped, and even commercialized for this purpose. However, it is only recently that HMDs like the Oculus Rift [1] the HTC Vive [2], and the Playstation VR [3] (PSVR) deliver practical immersive experiences, thanks to recent technological advances in display, GPU, and tracking technology. These devices stimulate our senses to make us believe we are present in a fully computer-generated world, a *virtual reality (VR)* [4].

In addition to transporting us to virtual worlds, HMDs can also transform our reality by overlaying helpful pieces of computer-generated content with information relevant to our physical world, which then becomes an *augmented reality (AR)*, as shown by smart glasses like Google Glass [5]. In some cases, these overlaid objects are anchored to a point in the physical space, seamlessly blended into the real-world and giving the illusion of being physically present, resulting in a *mixed reality (MR)*, a subset of AR, best characterized by devices such as Microsoft HoloLens [6] and other devices like Magic Leap.

While these three different *X realities (XR)* are often embodied by a head-mounted display (HMD) and share common technical challenges, they should not be conflated. Each XR technology has its own set of opportunities, applications, and tools. Between the three, it is easy for a newcomer to feel lost within the large amount of online resources. The goal of this article is to introduce two X realities, VR and MR, to researchers interested in building new applications and exploring the challenges these X realities bring, such as rendering offload, power efficiency, security, and privacy.

**TABLE 1. Minimum and desired requirements of an immersive head-mounted display**

| | Minimum requirement | Naked-eye judder-free acuity |
|---|---|---|
| Framerate | 90 fps with low persistence | > 300 fps |
| Field of View | 80 degrees | 160 degrees |
| Resolution | 1920 x 1080 per eye | > 4Mpixels per eye |
| Angular resolution | 10 pixels per degree | 60 pixels per degree |
| Motion-to-photon Latency | 20 ms | < 20 ms |
| Tracking precision | < 1 mm | < 1 mm |

## VIRTUAL REALITY

Thanks to devices such as the Oculus Rift, the Playstation VR, and the HTC Vive, virtual reality is constantly making headlines, and those devices are the first to be successful in the mass market. They are different than their predecessors for a few reasons: a) they reached a price point that is expensive, but not outrageous; b) they are designed for home use; c) they feature extensive libraries, with more than 1000 titles for the Vive and the Rift, and more than 50 major titles for the PSVR; and d) their visuals are high-quality enough for use. Previous HMD devices were not usable because they often induced heavy *simulator sickness*, a set of symptoms similar to sea sickness. In an immersive virtual experience, the human brain interprets the HMD's visual and auditory stimuli as reality. However, if the quality of the stimuli is not high enough, it overwhelms the senses and the brain, producing simulator sickness. The quality of the stimuli needed for an immersive experience avoiding simulator sickness varies from person to person, but scientists at Valve [7,8] have empirically found that in addition to careful application design, an HMD must satisfy the minimum requirements described in Table 1. They found that while a framerate much higher than 90 is desirable to avoid an unpleasant effect known as *judder* (a mixture of smearing and strobing), as long as the display has a persistence of 1ms, it is possible to reduce smearing, and the amount of strobing at 90 fps is, in general, acceptable. In other words, the screen displays a new image every 11 ms, but the image only stays on the screen for 1 ms, preventing smearing afterimages in the retina as the user's eyes move. They also discovered it is possible to increase the field of view at low cost by using lenses very close to the user's eyes. This increase in the field of view comes at a price, a pincushion distortion, which is easily fixed by applying the reverse distortion (barrel) to the rendered image [9].

Even the highest image fidelity would not be enough to deliver a sickness-free immersive experience without accurate tracking. Each major HMD is capable of tracking with a precision of less than a millimeter, but each HMD designer used a different mechanism in addition to *inertial measuring units* (IMUs) which are sensors composed of accelerometers, gyroscopes, and magnetometers, whose drift error makes them insufficient to deliver precise tracking.

The HTC Vive uses *lighthouse tracking* [10], which, as its name suggests, floods the room with light (LEDs and lasers) using two base stations, hitting the photosensor-covered Vive headset. The Vive then can count the time between the beacon (IR LED) hitting the headset and the sweeping beam (laser) hitting any of the photosensors. Because the Vive knows the position of the base stations in advance, the Vive can calculate its own position and orientation (i.e. its *pose*) using the position of the base station, the position of the photosensor hit by the beam, and the time the sensor is hit. Vive's solution is a cheap and very accurate way to allow tracking for a full room (*room-scale tracking*). However, the vast number of photosensors adds to the device's weight, making it heavier than other VR HMDs.

The Oculus Rift uses *constellation cameras* [11], in which the headset emits light from a series of IR lights on its surface. These lights, resembling a constellation, are captured by one or more cameras and processed by the Oculus software to determine the position. This approach adds less weight to the device, requires only one camera, and delivers great results for VR

**TABLE 2. Comparison of major head-mounted displays**

**Commercial Devices**

| | Oculus | Vive | Gear VR | PlayStation VR | HoloLens |
|---|---|---|---|---|---|
| Type | Tethered Virtual Reality | Tethered Virtual Reality | Mobile Virtual Reality | Tethered Virtual Reality | Mobile Mixed Reality |
| Suggested scenario | Seated / standing High Quality VR | Room scale High Quality VR | Seated / Standing Mobile VR | Room scale VR | Free-range Mixed Reality |
| Image |  |  |  |  |  |
| Resolution | 2160 x 1200 | 2160 x 1200 | 2960 x 1440 (Galaxy S8) | 1920 x 1080 | Not public |
| Framerate | 90 | 90 | 60 | 90 | 60 (individual RGB colors at 240 Hz) |
| Field of view | 110° | 110° | 110° | 100° | < 80° |
| Tethered | Yes | Yes | No | Yes | No |
| Room size | < 20 x 20 ft. | < 8 x 8 ft. | Standing / sitting | < 8 x 6 ft. | Not limited to a room |
| Tracking mechanism | Constellation Cameras  | Lighthouse base stations  | Phone sensors only  | PS Move (Optical LED tracking)  | Sensor bar, environment cameras  |
| Required hardware | PC with Nvidia GTX 1060 or better / AMD RX480 or better | PC with Nvidia GTX 960 / AMD FX4350 or better | Samsung Galaxy S6, S7 or S8 | Playstation 4 / PS4 Pro | None |
| Platform | Windows | Windows, Very limited Linux support | Android | Playstation 4 / PS4Pro | Windows |
| Price | $499-697 | $799 | $129 | $499 | $3000 |

experiences where the user is sitting or standing without moving. However, it is more susceptible to *occlusion* (obstructions to the line of sight) making room-scale VR difficult. This problem can be mitigated by adding two or more additional cameras, but makes the solution less practical than using lighthouse base stations.

HoloLens and the upcoming Windows Holographic VR headsets provide tracking within the device without requiring external equipment, unlike the Vive and the Oculus. While other untethered headsets, like Samsung's Gear VR and Google's Daydream View, only use the internal phone sensors as an IMU, the Windows Holographic HMDs use a sensor bar composed of proprietary *environment understanding* [12] *cameras*, a depth camera, an ambient light sensor, and a 2MP RGB camera. The environment understanding cameras provide a fixed location in space, assisted by the IMU, to produce a pose. This technology allows the user to move freely without needing to deploy cameras or sensors in a room before using the device.

While VR HMDs are mostly known as entertainment devices, virtual reality HMDs have many other promising applications. The immersion that VR provides enables *telepresence*, the feeling of being close to someone far away, which revolutionizes video chat services. This virtual feeling of closeness easily translates to social networks, as exemplified by Facebook's Spaces [13], resulting in virtual communities. Immersion is not only capable of bringing us closer to people far away, but allows us to experience the world with someone else's eyes and facilitates empathy. For example, it is possible to gain a better understanding of discrimination by impersonating a prejudiced group in the virtual world [14]. Virtual reality can also make daily activities more enjoyable. It is entirely possible to transform a stationary bike experience into a virtual race along the coastline or turn a history lesson into a virtual tour. Virtual reality can help us prepare for emergencies by simulating catastrophes, and it can revive cherished memories saved in panoramic videos.

The virtual reality HMDs that offer the best experience are tethered, with the most popular ones being the HTC Vive, the Oculus Rift, and Sony's PlayStation VR. Both the Vive and the Rift are designed to deliver the framerate and resolution necessary to avoid VR sickness for well-designed applications. Finally, the PSVR, with its more affordable price and the installed PlayStation user base, dominates the headset market despite its slightly lower visual and tracking quality. Most mobile VR headsets use smartphones to power the rendering, display, and tracking capabilities of the headsets, which can be as simple as a DIY cardboard box. However, most HMDs in this category often induce VR sickness, and their limited tracking restricts them to seated/standing experiences.

## MIXED REALITY

Mixed reality is now possible thanks to research in translucent displays made by companies like Microsoft, Magic Leap, and Avegant [15]. These displays make it possible to seamlessly overlay virtual content on top of the reality we perceive. While there may be other ways to achieve this effect, the first mixed reality, publicly available HMD, HoloLens, and the upcoming Magic Leap, rely on translucent displays. Unfortunately, the details of the technology behind those displays are not available to the public.

Like virtual reality headsets, mixed reality HMDs need to provide immersion and avoid simulator sickness. However, it is easier for these devices to avoid sickness, since the real world as perceived through the translucent display is not affected by resolution or framerate constraints. Furthermore, fixed objects in the real world serve as "anchors," which help reduce simulator sickness. As a see-through device, HoloLens is much less susceptible to simulation sickness than VR headsets because there is no latency in the real-world view, which always matches the stimuli provided by the vestibular system and other senses. However, the field of view of HoloLens is noticeably narrower than most VR headsets.

While the HoloLens price is still high and no other alternative is available, the potential unlocked by mixed reality drives many developers and researchers to build MR applications. Unlike VR, in mixed reality, it is possible to selectively enhance, modify, or even remove portions of reality while the user interacts with the real world. For instance, mixed reality can bring relief to injured or disabled patients by presenting them with a modified reality in which their injuries are gone, providing an intense form of cognitive distraction [16] relieving their pain, and even accelerating their rehabilitation without interrupting their daily activities (Figure 1). The effects of immersion on the human mind are very powerful and are the subject of active study, opening the door to more applications as they are better understood. Mixed reality enables another important scenario, task guidance. By understanding what the user sees, an application can instruct users on how to build a piece of furniture or change a flat tire. Mixed reality can improve a traveler's experiences by overlaying translated text and speech when visiting a foreign country, as well as identifying helpful markers or information for tourists. Mixed reality has the potential to change office work forever by replacing physical monitors with custom-shaped and resizable virtual monitors, while allowing the user to seamlessly interact with the physical world. It is possible to use MR to visualize objects and people on physical spaces before investing in getting them there. For example, Lowe's [17] effort to use MR for home renovation allows customers to interactively visualize different kitchen options in a real, physical environment. Similarly, Cirque du Soleil is using MR [18] to design sets and plan shows, easily visualizing props and dancers in the set without requiring them to be there. At this article's time of writing, there are more than 200 publicly available applications for HoloLens. I believe as more MR devices become available and prices drop, we will see many more.

**FIGURE 1.** A patient trying out the Gear VR.

## OTHER DEVICES

In addition to VR/MR headsets there also are other devices that do not quite fit any category. Among them are those used for First Person View (FPV) navigation of drones and other unmanned vehicles. These headsets add an element of immersion to FPV navigation, enhancing the user experience. Several manufacturers, like Fat Shark, Avegant, and drone manufacturer DJI, build these headsets. Unfortunately, the fast motion of the drones, higher motion-to-photon latency, and lower resolution make these headsets prone to simulator sickness. However, many drone racers and enthusiasts have been able to overcome sickness through repeated exposure to the headsets, or they mitigate the effects by focusing on the horizon.

A wide variety of non-headset devices used for VR and MR also exist. For example, omni-directional treadmills (Figure 3 Virtuix Omni treadmill) are used to navigate a large virtual world without requiring a large physical space. VR cameras are also important non-HMD devices. Google and Facebook have presented cameras [19, 20] (Figure 2) that capture 360° video ready for consumption on VR headsets.

## JUST THE TIP OF THE ICEBERG

Head-mounted displays have finally enabled immersive experiences without introducing unmanageable levels of simulator sickness. However, the experience is far from being sickness-free and indistinguishable from physical reality. As Chet Faliszek, former Valve's frontman, said "[In VR] We're at Pong level." Even the highest resolution VR HMDs are far from the visual acuity of the naked eye, 20/20 vision (see Table 1). Apple


**FIGURE 2.** Facebook Surround 360 Camera


**FIGURE 3.** Virtuix Omni treadmill


**FIGURE 4.** TPCast wireless add-on for the HTC Vive

popularized the term "retina" display to denote a screen whose resolution matched the angular resolution of a healthy eye, one arc minute (60 pixels per degree). For a phone held at 12 inches away from our face, covering a small portion of our field of view, a resolution of just 960 by 640 was enough. However, for HMDs that cover over 100 degrees, like the Vive or the Rift, the necessary resolution is over 4 Mpixels per eye. Unfortunately, their resolution is far from hitting that mark, delivering instead around 10 pixels per degree. While this is enough to avoid simulator sickness, it is not high enough to allow the user to read from a virtual sheet of paper at arms' distance using a regular font size. The refresh rate of those devices introduces blurriness and judder. The use of low-persistence displays mitigates the former, but not the latter. To fully avoid both, a refresh rate of 300 FPS is necessary, and a higher rate is required for higher resolutions [21]. Tethered setups present a non-negligible tripping hazard and constrain the usage area to the length of the cable. However, untethered devices are more prone to simulator sickness, have limited graphic capabilities, and short battery life. There is still progress to be made before we have a completely comfortable, always-on, untethered, fully immersive, and sickness-free experience.

## RESEARCH CHALLENGES

The technological advances required to bring virtual and mixed reality from usable HMDs to devices that could be worn all day are very diverse and require close collaboration across different fields and disciplines. Some of those fields are physics, psychology, and medicine, which study problems, such as understanding the causes of simulator sickness, the sensitivity of the human visual system to different stimuli, improving the perceived resolution of an HMD by improving its optics, etc. Similarly, within computer science, the fields of computer graphics, computer vision, and HCI study problems, such as improving the quality and detail of virtual and mixed worlds, the development of user friendly interfaces for HMDs, and faster detection and recognition of objects in video feeds. While the efforts in these directions have a profound impact on the state of VR and MR, I will only describe in detail some of the challenges that VR and MR pose in systems and networking.

### Computation and Rendering Offload

Building an HMD that can deliver high-quality VR experiences with an acceptable latency and battery life is likely to require offloading of most of the computation and rendering to a powerful computer. Delivering a wireless experience to the headsets currently available has been solved by commercial products using millimeter-wave radios like the TPCast [22] (Figure 4). However, doing so at the resolutions and framerates required for a judder-free, blur-free, full visual acuity experience may require bitrates higher than those supported by even 60 GHz wireless standards [23, 24]. To support those experiences wirelessly, it is necessary to build faster and more efficient compression, improve wireless technologies to deliver higher bitrates at lower latencies, and empower mobile devices to pump massive amounts of data from the NIC to the display with minimal delay.

Alternatively, it is possible to offload to the cloud [25]. Cloud offload, in addition to the challenges present in wirelessly offloading to a nearby device, introduces prohibitive amounts of latency. While techniques such as prediction, speculation [26], caching [27], and image-based rendering [28, 29] can be used to hide latency, they also introduce undesirable visual artifacts and increase the overall bandwidth requirements. Building or improving latency-hiding techniques will play an important role in enabling VR/MR support in the cloud.

### Live Content

There are great opportunities for live content in VR. Experiencing live content through a VR HMD can immediately teleport a user to a remote physical location. Unfortunately, live content is currently limited to 360 degree video. As a panoramic video, it does not offer 6 degrees of freedom nor parallax, only allowing rotational head movement. Companies like Facebook, 8i, and Lytro have recognized this problem and are working on a solution. Facebook recently presented a sparse lens solution camera, while Lytro [30] is looking instead at light fields (the direction that the rays of light travel in space), and 8i [31] is working on holograms that can be overlaid on 360 degree videos.

### Security and Privacy

Nascent technologies such as VR and MR are vulnerable to security threats and privacy risks. Most HMDs, especially those used for MR, constantly capture potentially sensitive input, such as location information and audio and video feeds. Users of HMDs are prone to involuntarily leaking the sensitive information surrounding them by carelessly wearing the HMDs around sensitive information (documents, photos, whiteboards, etc.) [32] Similarly, they are also vulnerable to attacks that alter their perceived reality. For example, an attacker could alter the output of a mixed reality car application, interfering with the driver's ability to focus on the road [33]. Another attacker could simply replace the text in a mixed reality application without informing the user, misleading the user to believe what they read was really written in the physical world. It is also not hard to imagine general attacks that distort the output of an HMD to induce VR sickness, scare the user, or display misleading information. As the popularity of these devices grows and they become more widely available, the likelihood of attackers exploiting these vulnerabilities will increase.

### Power Consumption

VR and MR are wearable technologies. Ideally, users would wear them for several hours, or possibly full days, when using AR and MR technology. However, many components of HMDs are power-hungry, and while the consumption of the GPU and CPU can be mitigated through offload, it would not help reduce the energy consumption of the display. Reducing th0e energy consumption of the display and tracking are important challenges to overcome. Reducing the power consumption of OLED devices is not a new problem [34], but doing so without severely reducing immersion or introducing simulator sickness is a challenge [35]. Even small changes to the properties of the display image can have severe effects, for this reason, it is important to carefully validate their effectiveness with user studies.

**I'VE BARELY UNVEILED THE TIP OF THE HMD ICEBERG. IT'S AN AREA IN ACTIVE DEVELOPMENT; NEW APPLICATIONS, DEVICES, AND TECHNOLOGIES ARE REVEALED EVERY WEEK.**

## BUILDING YOUR FIRST APPLICATION

Once you have chosen your headset, it is very easy to build an application. Most VR and MR applications are built using *game engines*. These engines were originally built to simplify the development of videogames by abstracting away low-level aspects such as rendering, shading, physics, and input handling. Game developers used this engine to focus on details specific to their game instead of spending time on details common to most games. VR and MR headsets support these engines for the same reason, making it very simple to build applications for them. One of the most popular engines, Unity, has full support for Rift, Vive, GearVR, Daydream, and HoloLens development. It also makes it easy to build applications supported on multiple headsets. Unity is available for free and includes extensive demos and tutorials for building simple games and VR applications. It is easy to get started with Unity by using the Roll-a-ball Tutorial (https://developer.oculus.com/documentation/unity/latest/concepts/unity-integration-tutorial-rollaball-intro). With Unity, transforming an existing 3D game project into a VR or MR project is uncomplicated. It is as simple as replacing [36] the default camera with one of the specialized VR or MR cameras for Oculus [37], Vive (available as the SteamVR [38] plugin in the Unity asset store), and HoloLens [39]. Unity presents these cameras as objects whose properties expose the orientation and position of the HMD. Furthermore, Unity provides developers with an asset store, where they can acquire a variety of resources like 3D models, audio tracks, scripts, and even already complete games (free and paid).

## RESEARCH TIPS AND TRICKS

Building and evaluating a research prototype often requires a finer control of the execution, detailed power measurements, and using the devices in scenarios not explicitly supported by the manufacturer. I would like to share some tips and tricks I have learned after working with HMDs for the last few years.

**Native SDKs.** Both the Rift and the Vive provide C/C++ APIs and provide the source to the APIs. Unfortunately, neither provides the source to their respective runtimes, which access and control the individual sensors. However, by using the APIs, it is possible to have full control of the render pipeline and integrate custom DirectX, Vulcan, or OpenGL code. Additionally, Valve provides the source for the Vive's Unity Plugin, which can be modified to trick Unity into believing a physical HMD is connected. Doing so can be useful for device emulation or remote rendering.

**Tethered HMDs in untethered scenarios.** I have found it useful to use tethered HMDs in untethered scenarios. It is possible, for example, to plug them to ultra-compact, Intel-powered Windows machines, like the Compute Stick or the Skull Canyon NUC. Using the C/C++ APIs, it is possible to render to these devices even though they do not meet the minimum requirements. Older version of the Rift, like the DK1 and the DK2, are easier to "hack" with these mechanisms. It is possible, for example, to use off-the-shelf 60 GHz WirelessHD transmitters, like the DVDO Air3C Transmitter, to wirelessly hook an Oculus DK1 to a render machine and test wireless VR on a real headset before you can get one of the coveted TPCast wireless adapters for the Vive.

**Power measurement.** Measuring power is simple for most HMDs since many draw power through a USB port. Hardware power monitors like the Monsoon make this very simple. Other devices, like HoloLens, provide instrumentation APIs that give detailed information about power consumption. However, other devices like the Vive that do not use USB and draw a large amount of power even when idle are more challenging. It is possible to use power meters like WattsUp, but the accuracy is much lower than that of the Monsoon.

**Measuring simulator sickness.** When measuring the quality of a VR or MR experience, it is necessary to ensure that it does not induce simulator sickness compared to a commercial baseline. The standard way to measure simulator sickness is through user studies that include the well-known Simulator Sickness Questionnaire (SSQ) [40].

## CLOSING WORDS

I've barely unveiled the tip of the HMD iceberg. It is an area in active development; new applications, devices, and technologies are revealed every week. While many challenges have been solved, bringing the technology to a place where it can be enjoyed by the public, there is so much more to do. While I focused mainly on the challenges behind a fully immersive experience, the opportunities in building new applications, content, and interactions using VR or MR are just as vast. Actively trying different devices and build applications while working with experts in different fields or disciplines is the best way to find new applications or identify aspects that can be improved. The technology is very exciting and fun to play with, and the possibilities of identifying a new challenge in a new area like this are enough to justify the time spent exploring.

### Acknowledgements

My work with virtual and mixed reality wouldn't have been possible without the brilliant contributions and talent of many colleagues, including Bernhard Reinert, Kevin Boos, Tan Kiat Wee, Rajesh Balan, David Chu, Johannes Kopf, Tobias Ritschel, Yury Degtyarev, Alec Wolman and Landon Cox. ■

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