The RealityMashers: Augmented Reality Wide Field-of-View Optical See-Through Head Mounted Displays

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Figure 1: Users wearing (A) the Compact RealityMasher and (B) the Windows RealityMasher. (C) The COMRADRE Lab space

Abstract

Optical see-through (OST) displays can overlay computer generated graphics on top of the physical world, effectually fusing the two worlds together. However, current OST displays have a limited (compared to the human) field-of-view (FOV) and are powered by laptops which hinders their mobility. Furthermore the systems are designed for single-user experiences and therefore cannot be used for collocated multi-user applications. In this paper we contribute the design of the RealityMashers, two wide FOV OST displays that can be manufactured using rapid-prototyping techniques. We also contribute preliminary user feedback providing insights into enhancing future RealityMasher experiences. By providing the RealityMasher's schematics we hope to make Augmented Reality more accessible and as a result accelerate the research in the field.

Index Terms: H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented and virtual realities; H.5.3 [Information Interfaces and Presentation]: Group and Organization Interfaces—Collaborative computing

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1 Introduction

Augmented Reality (AR), pioneered by Ivan Sutherland in the 1960s [14], is a view of the environment where the physical world is enhanced and supplemented by virtual objects. The resulting augmented view is possible due to display technologies that can render virtual objects superimposed on the physical environment. Albeit far from it, the ultimate goal of these technologies is the juxtaposition of the physical and virtual world in such a way that the digital and physical objects are indistinguishable to the naked eye. AR technologies are revolutionizing the way we interact and perceive the world around us, with applications on every scientific domain.

One of the most promising technologies for commercial AR is near-eye Augmented Reality, which uses OST head-mounted displays (HMDs) (*i.e. smart-glasses*), to combine the view of the physical with the digital world. Using a half-transparent mirror (beam splitter) that is placed in front of the user's eyes, the real world can be seen without loss of the eye's natural field-of-view (FOV), while the digitally rendered virtual content appears through the use of reflections. The human eye's FOV is 200° horizontally and 135° vertically (both eyes) [4], however the best available HMD today has a diagonal FOV of 40°, which limits the permitted augmented area. To put it another way, only 15% of the eye's horizontal FOV can be augmented, which restricts the possible AR domains and applications. However, wider FOVs has been shown to improve the performance [5] and accuracy [18] of distance judgments as well as increase the sense of presence [11], therefore improving AR experiences.

Some other equally important considerations for commercially available AR headsets are the cost, the access to the headset's hardware and raw sensor data, and the system's mobility. Commercially available HMDs today lack a processing unit and therefore need to be tethered to a PC or laptop, reducing the user's mobility and real-life use. Additionally there is no easy way to modify the hardware or get access to the sensor raw data, as it is usually hidden behind

APIs. The above are very important considerations, particularly in research, when selecting AR HMDs, as hardware and software flexibility is needed.

In this paper we describe the design and implementation of two 45° diagonal FOV OST displays that are low-cost, can be manufactured using rapid-prototyping techniques and are geared toward the research community, called the RealityMashers (Figure 1).

Contributions

In summary, we contribute the design of two novel 45° diagonal FOV OST displays that can be easily manufactured using rapid-prototyping techniques and used for research in AR experiences. Specifically, we contribute:

- The design and implementation of a 45° diagonal FOV untethered OST HMD and a 45° diagonal tethered OST HMD, called the Compact RealityMasher and the Windows RealityMasher respectively
- The software and hardware architecture that enables quick rapid prototyping of AR experiences and applications
- A set of considerations that frame the design space for implementing wide FOV experiences

2 Related Work

Our work builds on previous research in Augmented Reality and Optical see-through displays.

2.1 Augmented Reality

Milgram et al. describe Augmented Reality as the technologies that augment and juxtapose the physical space with digital objects [9]. The first AR devices used bulky HMDs [14] that overlaid the rendered graphics using OST or video see-through displays. OST HMDs use optics to display the physical world and usually involve a beam splitter that serves a dual purpose: it allows light from the outside world to pass through while redirecting light from the display to the eyes. In contrast, video-see through HMDs capture the environment using one (or more) cameras and combine it with the virtual content. Other AR technologies include Handheld [16] and Spatially Augmented Reality (SAR) [12]. Interested readers can read Krevelen's and R. Poelman's survey of the technologies, applications and limitations of AR [15].

2.2 Optical see-through Displays

Optical see-through HMDs display the virtual content without encumbering the view of the physical environment. The FOV of the physical world is unchanged while the FOV of the virtual content depends on the optics and technology being used.

During the last 50 years a plethora of technologies [6] has been invented for optical see-through HMDs, however the mirror beam splitter, also known as a combiner, still remains one of the simplest and most effective ways to build an AR display with a sufficient FOV. A beam splitter allows the environmental rays to pass through to the eye, while reflecting a displays computer generated images. Additionally, placing a lens between the combiner and the display makes the image to appear further away, allowing the pupils to focus more comfortably.

2.2.1 Widening the FOV

The FOV of an OST HMD defines *how much* of the virtual content a user can see as well as the portion of the physical world that can be augmented. Therefore a wider FOV is desirable as it has been linked to improved AR experiences: it improves performance [5] and accuracy [18] of distance judgments in AR experiences, and creates an increased sense of presence [11].

2.3 Trackers

There has been a lot of research in tracking technologies for HMD systems, with researchers focusing to optimize latency, update rate, accuracy, and tracking volume. A good tracking system is essential for proper registration of virtual content to the physical environment. Registration here means that the virtual content appears to be present in the physical world and does not move as the user walks around. Trackers can be magnetic, acoustic, mechanical or optical, with the latter usually preferred as it has many advantages over the other systems: high update rates, not prone to environmental interference (ex. metals interfere with the magnetic trackers), larger tracking volumes and are untethered.

There are a variety of off-the-shelf solutions that exist for optical tracking systems such as ARToolkit[1] and ARTag[2] that use simple 2D markers, like QR codes. One of the most widely used optical tracking system is OptiTrack[3] due to it's robustness and performance. OptiTrack consists of a set of cameras that track infrared retro-reflective markers, which are usually placed on HMDs for accurate 6DOF tracking.

A complete survey of HMD tracking technology is beyond the scope of this paper and we encourage interested readers to refer to Azumas [2], and Bhatnagars survey [3].

2.4 Graphics Software and Hardware

The graphics software and hardware piece all of the above together, and for most AR systems, a laptop or a mobile phone serve as the hardware platform for rendering the content. To achieve spatially registered content, special software packages are used that support AR devices and technologies. For instance, Studierstube [13] is a C++ framework for building collaborative user interfaces in AR, with support for a variety of display technologies (HMDs, projection based, etc.). It supports multiple users and is based on a heterogeneous distributed system that is based on a shared scene graph. However, while open-source, it is difficult to maintain and does not support mobile phones or recent technologies like depth cameras.

Commercially available game engines have recently been used to develop AR experiences, due to their support communities, powerful rendering engines, multiple platform support, and ease of use. Unity3D[4] features a visual editor for authoring the application, scripting support for developing custom behaviors and support for multiple AR platforms. As a result, researchers have used it to create frameworks and toolkits that facilitate AR development. For instance, ARTiFICe [10] is a framework based on Unity3D that enables the development of distributed and collaborative AR applications. It supports a variety of AR setups and was used in teaching by 97 students that developed a variety of AR applications [10].

3 Motivation

Barriers to the wide adoption of Augmented Reality are the high cost of AR devices and the limited flexibility in hardware and software tinkering. When prototyping new experiences the ability to easily interchange one of the four main components of an AR device (displays, input devices, tracking, computing unit) is very crucial. However, commercially available AR devices are closed hardware and software systems that do not allow that flexibility. Our goal was to design an easily replicable OST HMD and design an experimental space that allows for rapid prototyping of AR experiences. Our design enables interchangeability in any of the four main components and therefore allows for infinite experimentation, unlocking a plethora of research opportunities. Our hope is that

[1] http://www.hitl.washington.edu/artoolkit/

[2] http://www.artag.net/

[3] http://www.optitrack.com/

[4] 9/21/15, http://unity3d.com/

the RealityMashers' design will facilitate the acceleration of AR research and foster collaboration among research institutions.

Figure 2: The COMRADRE Lab

To this end we funded the Center Of Mixed Reality and Advanced Development and REsearch (COMRADRE) Lab 2, an experimental space for rapid prototyping of AR technologies, applications and experiences. The space was designed to facilitate research and development of AR displays, tracking, input technologies and computing paradigms in social, collaborative indoor settings. To enable a larger pool of applications, we prototyped two wide FOV headsets: a lightweight, untethered and portable OST HMD, the Compact RealityMasher and the Windows RealityMasher, an OST HMD that is powered by a backpack high-end gaming laptop.

4 REALITYMASHER SYSTEM OVERVIEW

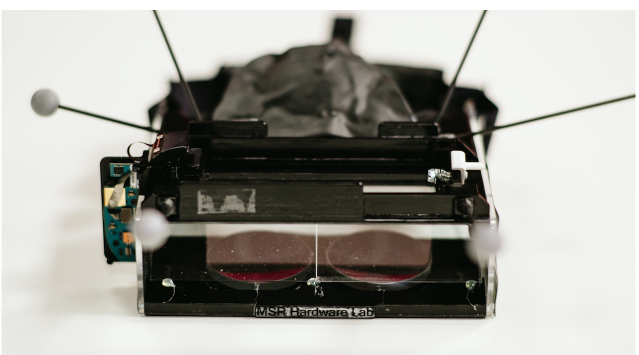

Figure 3: The Compact Reality Masher

The tracking, mechanical design and optics of both the Windows and Compact RealityMasher are identical with the only difference being the display being used and the computing module that runs the device. The Compact RealityMasher (Figure 3) uses Samsung's Galaxy S6[5] smartphone as the display and processing unit and therefore the AR experiences are untethered, allowing for complete freedom of movement. In contrast, the Windows RealityMasher (Figure 1B), uses an HD AMOLED as the display and a backpack laptop (2014 Razer Blade Pro - Intel Core i7-4700HQ, 16GB DDR3 RAM, Nvidia GeForce GTX 860M) for processing and rendering. Although the backpack is not as comfortable as the untethered RealityMasher, the graphics and performance of the system are superior because of the improved CPU and GPU (for comparison see Table 1) of the laptop. Furthermore because of the larger display unit (5.7 compared with 5.1 inches) the system also benefits of a 4° increase in the horizontal FOV.

[5]http://www.samsung.com/us/explore/galaxy-s-6-features-and-specs/

To enable collocated and shared experiences, five Compact RealityMashers and one Windows RealityMashers were constructed.

Table 1: Specs of the Windows and Compact RealityMasher

Specifications	Windows	Compact
Display	OLED	AMOLED
Display Size	5.7 in	5.1 in
Resolution	1920x1080	1440x2560
CPU	Intel Core i7-4700HQ	Quad-core 1.5GHz Cortex-A53
GPU	Nvidia GeForce GTX 860M	Mali-T760MP8
RAM	16 GB	3 GB
Horizontal FOV	40°	36°
Diagonal FOV	45°	45°
Extra Devices	Leap Motion	N/A

4.1 Tracking

All headsets were equipped with unique 3D patterns of retro-reflective spheres that were tracked using the motion capture OptiTrack Prime series cameras[6] that can track up to 2,000 retro-reflective markers. The cameras were ceiling mounted (Figure 2) and in order to cover the $918ft^2$ space (36x25.5 ft) 6 Prime 41 cameras (180FPS, 5.5ms latency) and 6 Prime 17W (360FPS, 2.8ms latency) were used. The cameras were connected to a Windows 8.1 PC (Xeon E5-1620V3 3.5 GHZ, 16GB RAM, Nvidia GTX 980) running OptiTrack's Motive[7] software.

The position, yaw, roll and pitch of the rigid bodies gets broadcasted over multicast through a middleware software that runs on the OptiTrack PC and connects to the Motive software. To avoid network congestion, the software only transmits data for rigid bodies that moved by at least 0.5mm compared with the previous frame. The data is packed in a binary format that uses a fixed-size binary buffer and contains the rigid body tuple, the position vector, and the rotation quaternion with a 4 byte precision. The middleware software throughput was set at 60 frames per second. The headsets connect to the OptiTrack PC over wifi through a Netgear Nighthawk AC1900[8] wifi router.

4.2 Rendering

Unity3D 5 game engine was used for rendering the headset's content. Because of it's powerful and flexible game editor, Unity allows for rapid prototyping of AR experiences using state of the art animation, rendering and lighting effects, allowing researchers to focus on the experience. Lately, game engines are increasingly been used by researchers to design and develop 3D experiences [7].

4.3 Mechanical Design

The frame of the RealityMashers was designed to provide a lightweight, modular housing for the optical array, display and Inertial Measurement Unit (IMU). The design supports AR by minimizing any features that would impose on the users forward or peripheral vision. Clear polymer side plates provide structure while not occluding the natural field of view (Figure 4).

The base and top parts were 3D printed using a combination of Polyjet and Fused Deposition Modeling (FDM) technology, while

[6]https://www.optitrack.com/hardware/

[7]https://www.optitrack.com/products/motive/

[8]http://www.netgear.com/home/products/networking/wifi-routers/R7000.aspx

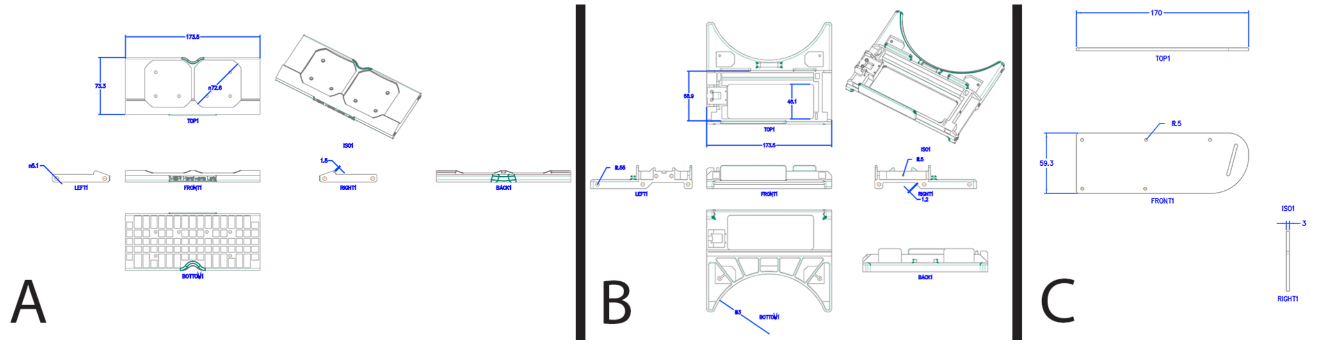

Figure 4: The mechanical design of the Reality Masher. (A) Bottom view, (B) Top view, (C) Side panels

for the side elements laser cut plastic sheet was used to maximize the horizontal FOV. The parts were assembled using common threaded fasteners and inserts. The HMD size is 173.5mm x 73.5mm and weighs 450gr. To improve tracking accuracy and produce a smoother experience, the MPU-6500 Inertial Measurement Unit (IMU) was used (see 4.4).

4.3.1 Optics

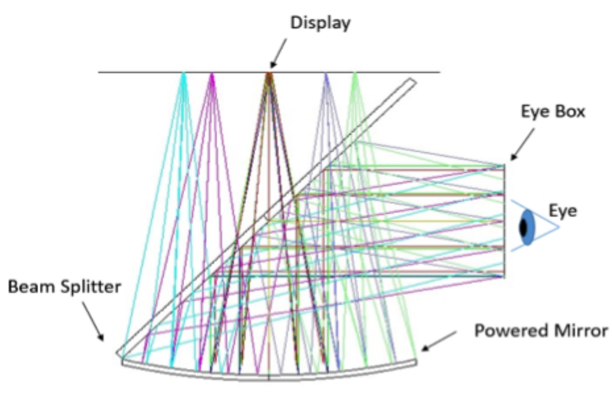

Figure 5: Birdbath Design

The optical design uses a 60mm x 85mm plate beam splitter that allows the light from the top-mounted bottom-facing display to pass through it, reflect on a 50mm focal length spherical mirror and on the beam splitter's other side to the viewer's eyes (Figure 5). This design is often referred to as Birdbath [8] and is very popular among AR devices. A ZEMAX model of the system was also constructed to layout the design and evaluate its performance. The headset mounting was designed for an eye relief of 20 to 25mm. The resulting FOV of the OST varies slightly from person to person depending on their eye relief and it was measured at 36° horizontal (45° diagonal) for the Compact Reality Masher and 40° horizontal (45° diagonal) for the Windows RealityMasher.

4.4 Sensor Fusion

A 6DOF estimate of the HMD in a known coordinate frame with no drift or temporal lag from its true value is needed to render virtual content that appears spatially registered. However, while the OptiTrack system does give accurate pose estimates at 60 FPS, there still is a temporal lag caused by computation time (on the OptiTrack PC that filters and transmits the data, as well as locally on the headsets being on the receiving end) and wireless communication transfer. This lag is small (under 1ms), however it produces a noticeable jitter effect under any rotational velocity. This is due to the fact that micro head movements still cause significant changes to the projected pixel positions of 3D objects on an image and any lag or drift will be immediately noticeable. To account for this the a high speed IMU (MPU-6500) was mounted to the headset and used to perform late stage re-projection, providing a rotation estimate that does not lag temporally.

To perform sensor fusion we use a simple approximation to the Kalman Filter. We propagate our estimate using filtered IMU sensor measurements under a known system model. We then use spherical linear interpolation to update the estimate with information from the OptiTrack system. The interpolation parameter approximates the Kalman Gain and was calibrated manually. This update is performed only when rotational velocity is small enough that the OptiTrack measurement can be considered accurate temporally. In order to use the OptiTrack and IMU measurements together the rotational offset between them needs to be accurately calibrated. This is done offline in a calibration procedure where we compare rotation estimates generated by the IMU with those generated by the OptiTrack system.

We do not use the IMU for position estimation as the position estimate will drift quickly from its true value. In addition the fusion with OptiTrack values was unnecessary as small changes in position do not produce significant changes in projected pixel values.

4.5 Kinect Array

A Kinect for Xbox One[9] array was constructed for full body skeleton tracking and 3D sound localization. The Kinect for Xbox One is a markerless body and skeleton tracking system that tracks users using a time-of-flight camera. The array consists of four Kinects mounted on the ceiling of each wall and positioned for maximum room coverage with minimum sensor overlap. Each Kinect is connected to a dedicated computer (Intel NUC Kit NUC5i3RYH[10] - Intel Core i3 2.1GHz Dual Core, 16GB DDR3 RAM, Intel HD Graphics 5500) that broadcasts the joint skeleton data over the network. The joint data is packed into multicast UDP packets and transmitted over the network.

Calibration of the Kinects and the OptiTrack system into the same reference frame is manual with the help of an OptiTrack tracked 30cm cube. The cube is placed within each Kinect's field of view and calibrated manually by looking at it through a RealityMasher while aligning the Kinect's depth data to match the cube's. The OptiTrack system is used as the main reference frame and the resulting world transformation is saved and applied to each Kinect frame.

[9] http://www.xbox.com/en-US/xbox-one/accessories/kinect-for-xbox-one

[10] http://www.intel.com/content/www/us/en/nuc/nuc-kit-nuc5i3ryh.html

4.6 Input Devices

To interact with the virtual objects, a series of different input device methodologies have been explored, as to enable interaction within the AR experiences.

4.6.1 Wand

For precise and finite control, five PlayStation 3 Move Motion Controllers[11] were used as wand devices. Each controller has a unique set of retro-reflective markers to enable 6DOF tracking (Figure 6) through the OptiTrack system. The devices connect over bluetooth to the OptiTrack PC, which collects all controller events (clicks, button ups and downs and analog trigger events) and broadcasts them over multicast to the network. Each UDP packet consists of a controller id and the corresponding event with end-to-end latency below 1ms.

Figure 6: The Wand input device

4.6.2 Leap Motion

For hand gesture interaction a Leap Motion controller was used. The Leap Motion was used only on the Windows RealityMasher (as it can only connect to a PC) and was mounted below the HMD (Figure 7 (E)). The alignment of the Leap Motions coordinate system with the OptiTrack's was manually done using the same method as the Kinect's (see 4.5), where Leap Motion's digital hands get aligned with the physical ones. However, the OptiTrack cameras interfered with the Leap Motion, as both use IR lighting for tracking, resulting in spotty hand tracking performance. Although we wouldnt recommend using a Leap Motion alongside an OptiTrack system, we found that enabling Leap Motions robust mode results in improved tracking performance.

4.6.3 Physical Props

For direct object manipulation physical props where used, resulting in more natural human-computer interaction. Cubes, rectangles, spheres and cars were equipped with unique marker sets and registered on the OptiTrack system, taking into consideration the physical shapes as to not hide the markers from the cameras.

5 Prototype RealityMasher Experiences

To evaluate the RealityMashers, we developed six AR experiences which explore the design space of wide FOV AR OST HMDs. Two of the experiences (*Visualizing Energy Propagation* and *Mathematics in AR*) were developed for the Windows RealityMasher while the rest used the Compact RealityMashers.

5.1 Compact Reality Masher Experiences

Embodied Social Interaction (Figure 7 (A))[17] explores new kinds of interactions by augmenting the user's actual physical body where collocated users can interact with each other resulting in different graphical outcomes. The **Extended Developer Workspace** (Figure 7 (B)) extends the traditional AR integrated development environment (IDE) by allowing the developer to design the experience completely in AR, encouraging rapid iteration of applications. **Augmento** (Figure 7 (C)) is a framework that enables the development of multi-user collocated collaborative, shared and private experiences and has been used in the development of four shared experiences. **TactileAR** is an AR experience for kids that integrates physical toys, and allows them to play in juxtaposition with the digital content, creating opportunities for collaborative play [1].

[11] https://www.playstation.com/en-us/explore/accessories/playstation-move/

5.2 Windows Reality Masher Experiences

Visualizing Energy Propagation (Figure 7 (F)) explores the visualization of otherwise invisible information about the environment, like energy propagation. In this experience, an array of microphones is used to extrapolate the location of sounds and visualizes the energy propagation by taking into account the room geometry. **Mathematics in AR** (Figure 7 (E)) is a gesture and voice-controlled application that uses the physical space around the user to plot mathematical objects—like functions and matrices—and perform operations.

6 Design Space Considerations

To help frame the design space we elaborate on three ways one can reason about the RealityMashers content and experiences.

6.1 Smartphone powered AR promotes mobility

The AR experiences that were developed engaged users into moving freely and using all the space's real estate. When designing the various experiences all developers preferred developing an AR application for the Compact RealityMasher over the Windows RealityMasher as mobility was more important than GPU and CPU performance. In fact none of the developers complained or asked for a more powerful smartphone. The only two exceptions to this observation were the *Visualizing Energy Propagation* and *Mathematics in AR* experiences. The former needed superior computational power in order to run the propagation models, while the latter required the use of the Leap Motion to track gestures, as it does not support smartphones.

6.2 Wider FOV enhances collocated collaboration

The wider FOV enhanced collocated collaboration as the FOV was sufficient to frame a user standing across the HMD with content rendered on top of them. This consideration pushed developers to design and support some kind of collaboration schema in their applications. In particular, we have identified three types of collaboration scenarios:

- **Shared Collaborative AR**. In this scenario all users wearing the HMD can see the same content but from their own perspective. *Embodied Social Interaction, Augmento* and *TactileAR* are utilizing this modality.
- **Private AR with Shared Views**. In this scenario the users have their own private AR experience but can share some of the content with other users. *Augmento* is an example of this modality.
- **Multi-user Private AR**. In this scenario the system supports multiple users at the same time, however each user has their own private AR experience that cannot be shared with others.

7 Preliminary User Feedback

We demonstrated the RealityMashers to 40 users, having them experience each of the developed applications for roughly 5 minutes. We focus our discussion here on the user feedback regarding the system.

Users were surprised by the wide FOV of the system and therefore by the amount of augmentation. Users were impressed by

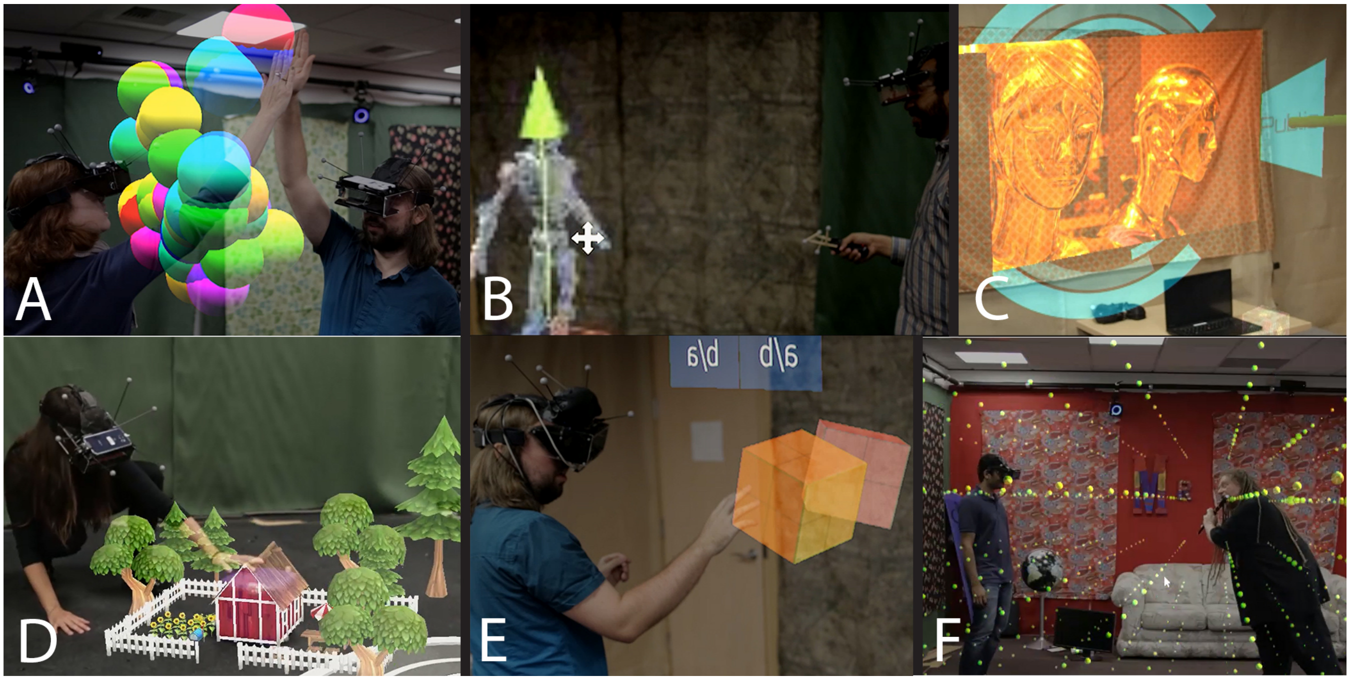

Figure 7: Reality Masher Experiences: (A) Embodied Social Interaction, (B) Extended Developer Workspace, (C) Augmento (D) TactileAR, (E) Mathematics in AR, (F) Visualizing Energy Propagation

the enhanced augmentation because of the wider FOV and enjoyed playing the games as now they could see (digital) enemies and (physical) users in the same frame.

Users also commented on the collaborative modalities of the system, appreciating the fact that they could experience simultaneously some of the applications (like the *TactileAR* and *Augmento* applications). Application developers reported that the collaborative modalities of the RealityMashers allowed them to demo their applications with larger groups of people, as they could experience AR at the same time from their own perspective. Furthermore, because of the ease of putting on/taking off the Compact Reality Masher, we observed that users could very easily experience the AR applications.

A game developed with the *Augmento* framework was the experience that resonated the most with our users. The subjects were very engaged during the game while making use of the entire lab space to run away from the attacking bunnies. However we did not observe any collaborative strategies among the players.

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