A Review of Current, Complete Augmented Reality Solutions

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***Abstract*—The extended reality market has rapidly grown with a wide range of products for not only Virtual Reality applications, but also for advanced and multiple forms of Augmented Reality. In this paper we review the currently available complete solutions for Augmented Reality, divided into the primary display techniques used: *Video See-through*, using cameras to capture the real world subsequently presented with virtual overlays on a handheld or headworn display, *Optical See-through*, using semi-transparent display to allow real world view together with the virtual augmentations, and *Projection-based AR* or *Spatial AR*, the use of projectors to display augmentations directly on top of surfaces in the room. First potential products were found using popular Internet search engines, after which products that are not complete solutions or not commercially available were filtered out. We present the different products together with a description of their presented or studied characteristics, and of their accompanying software solutions.**

***Keywords*-augmented reality; optical see-through; video see-through; head mounted; survey; mixed reality;**

I. Introduction

At the release of the HoloLens headset, the first complete, commercially available solution for Augmented Reality (AR), the bar for creating advanced AR application was suddenly lowered, opening up a whole new paradigm for visualization and interaction to all research disciplines, industries and even home users. Since then, the market has grown steadily and today, the number of available complete solutions for AR is large, including many different approaches and display technologies, and we judge that time is ripe for a review of the state of the market.

Purpose and target audience: The purpose of this paper is to provide a comprehensive list and review of complete solutions for AR that can be used by content providers or graphics and visualization researchers to implement AR applications. To be of interest here, the solution has to be *available* to non-experts, that is, available for download to a readily available system or on sale on the open market. Thus, the target audience is graphics researchers, professionals and developers that are not currently doing their primary work on AR technology, thereby being consumers rather than providers of AR technology.

Method: Potential products were found in an initial wide search, using popular Internet search engines. Then solutions not of interest for this review were removed: those that do not constitute a full solution, for example glasses, projectors or screens that need third party software to work as AR solution, and those that are not commercially available, for example prototypes, research, DIY or legacy systems. The remaining solutions were categorized based on use, type or underlying technologies, then analyzed with respect to their most important properties with respect to Augmented Reality.

II. Terminology and Categorization

The Milgram reality-virtuality continuum[1] is a well established model that goes from reality to *Virtual Reality* via *Mixed Reality* (MR), that is also further divided into *Augmented Reality* (AR) and *Augmented Virtuality* (AV). Since MR per its name cannot include the purely virtual space it has become increasingly common to use the term XR, for eXtended Reality, to signify everything in the continuum except pure reality. While being described by Milgram as part of a continuum, the actual implementation of on the one hand AR, virtual objects augmenting a real world, and on the other hand AV, real objects moving around in an otherwise virtual world, may be fundamentally different; in AR the real world is used as frame of reference, in which the user cannot teleport any more than they could without the display system, while AV renders real world views in a mostly virtual environment, thereby allowing both navigation metaphors and remote collaboration. The focus here is on technology supporting primarily the former, AR, the rendering of virtual objects in an otherwise real environment. For AV we refer the reader to VR solutions.

The most prominent differences found between the solutions stem from their applied see-through principles, so we chose to primarily categorize the solutions by the fundamental AR display principles of Milgram[1], *Video See-through* (VST) and *Optical See-through* (OST), extended with projection-based AR, also called *Spatial AR* (SAR)[2]. With VST a camera captures a video feed of the real world, which is then combined in software with computer graphics and presented on a display, either head mounted

DOI 10.1109/CW52790.2021.00015

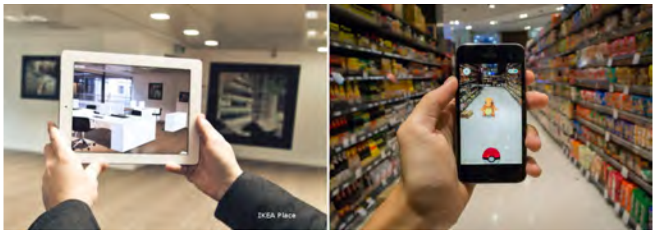

Figure 1. VST AR examples: *Ikea Place* lets users try furniture in their desired areas (left), and *Pokémon Go* a mobile game which lets players hunt virtual creatures (right).

(HMD), handheld or room mounted[3], see Figure 1. Using a video feed, the algorithms have full control over the visual integration, allowing full occlusion between virtual and real objects, and even advanced modification of real objects. Issues with VST displays are mostly associated with HMDs, including stereo calibration, camera or screen resolution and latency in camera imagery leading to vection and nausea. Also, the cameras mounted on a HMD cannot be co-located with the user's eyes, leading to a viewpoint parallax error[4]; as the users turn their head, the cameras move differently to the eyes, resulting in vection. This can be solved using mirrors[4], however we can disclose already here that none of the commercial solutions we have found apply this remedy. On the other hand, the resolution and latency problems are challenged by new products, as is presented below.

With OST AR there is a direct optical path of light from the world into the users' eyes and computer generated graphics are added to the view through some semi-transparent display, see Figure 2. With an optical view of the real world, the risk for cyber sickness is low and the resolution is optimal. However, common issues with OST displays include limited field-of-view (FoV) for the augmentation, accommodation discrepancy between real and virtual objects, limited brightness, poor contrast or color reproduction, and view alignment errors leading to graphics misalignment. More importantly, a traditional semi-transparent display cannot occlude the optical view, resulting in graphics looking like made of light, like a *hologram* in some popular media. This can be solved by introducing an occluding LCD mask (for example [5], [6]), however none of the commercial solutions apply this type of remedy. On the other hand, the manufacturers are slowly improving the FoV, and a solution to the accommodation issue have found the market, as you can read below.

With SAR, projectors are used to display augmentations directly on real objects, see Figure 3. Thus, the real world is fully immersive, the user is not required to wear or hold a display system and the system can be permanently installed in a dedicated work space. With graphics projected onto objects, however, common issues include brightness and color of the projection, occlusion of static or moving

Figure 2. OST AR examples: car heads-up-display which shows the road information (left), and an illustration of how Microsoft HoloLens projects the virtual objects onto the real world (right).

Figure 3. SAR examples: the *Pool Live Aid project* visualize the redirected path of a billiard ball on the table (left), and the *Sand-box project* provides an interactive topographic contour line visualization in a sand-box (right).

objects, as well as alignment and registration in projection mapping[7].

III. Solutions for Video See-through

With the VST AR the virtual augmentations are superimposed upon a recorded video of the real-world and the result is displayed on an opaque screen. Thus, the device needs to be either equipped with built-in RGB cameras, one for mono and two for stereo, or use a stream from one or two external cameras. Because of this, most tablet and phones, and in some cases even laptops, can be used as VST AR devices, but there are also solutions based on HMDs.

A. Hardware Solutions

Varjo XR-3 is, at the time of writing this paper, the only HMD designed to create AR with its video pass-through technology [8] (Figure 4). There are other HMDs with built-in cameras. However those cameras are mostly for awareness of the surrounding and although video pass-through is available on some of this devices it often has low quality and is not suitable for AR. The XR-3 takes advantage of low latency (<20 ms) video stream provided by its pair of 12-megapixel 90 Hz RGB cameras. The device comes with two OLED screens (one for each eye) with a resolution of 1920x1920 (completely square) at 90 Hz, covering only a central portion of the view. For the rest of the view, it also is equipped with an LCD with a resolution of 2880x2720 pixels for each eye. The combination of the latter screens, for both eyes, cover approximately 115 degrees of FoV. For tracking the device utilizes a fusion between its LiDAR and RGB cameras. It is also capable of the head tracking using the Ultraleap Gemini (v5) and 200 Hz eye tracking. The HMD device weighs 594 g plus 386 g for the included headband. The positional tracking is provided via Steam

DOI 10.1109/CW52790.2021.00015

Figure 4. Varjo XR-3 HMD; left: the device. Right: an example AR project captured from XR-3 display.

VR 2.0 tracking system and the Varjo inside-out tracking (Beta) which utilizes the RGB video pass-through cameras. However, the Steam VR base stations for tracking should be be bought separately.

The Varjo native SDK can be used to develop apps for the XR-3. It also supports OpenXR III-B which enables porting software into the device. There is also native support for Unity, Unreal Engine, and industrial 3D software such as Autodesk VRED, Lockheed Martin Prepar3d, VBS BlueIG and FlightSafety Vital. To use Varjo XR-3 headset and soft-warean accompanying Varjo Subscription has to be bought which will provide access to Varjo's proprietary XR/VR software.

HMDs designed for VR can also be used to create AR, but for this either an internal or an external RGB camera are required, or two for supporting stereo.

The ZED Mini from *Stereolabs* [9] is, to the authors' knowledge, the worlds first external camera specifically designed for AR (see Figure 5). The camera can be attached to VR headsets such as *Oculus Rift* and *HTC Vive* using a mounting accessory. The camera provides stereo video pass-through, real-time depth mapping and environment mapping. The stereo cameras are each capable of transmitting videos of 2200p at 15 fps, 1080p at 30 fps or 720p at 60 fps. The device is also capable of streaming video over IP. The stereo depth sensing is ranged from 0.1 to 15 meters and has an FoV of 90 degrees horizontal, 60 degrees vertical, and 100 degrees diagonal at up to 100 Hz. ZED Mini is equipped with accelerometer and gyroscope and is powered via USB while it will weigh 63 grams.

The camera comes with their own software, ZED SDK, which is available for Windows, Linux and Nvidia Jetson. It contains all the libraries that powers the camera along with tools to use its features and settings. The SDK supports C++, Python, and C# development and can be interfaced with multiple third-party libraries and environments such as ROS, OpenCV, Docker, Unreal Engine, Unity, MATLAB, etc. There are many tutorials and code examples available to work with the SDK or the plugins.

B. Software for Handheld Devices

There are a number of available AR software solutions that can be used to turn a camera-equipped phone or tablet into a handheld AR device. Here, however, we consider only software that requires no additional implementation of AR technology and no or very little understanding of the implementation details that are required for AR.

Figure 5. ZED Mini Camera; left: the camera is mounted on a *HTC Vive* VR headset. Right: an example project created by the Zed Mini which turns the room into a battlefield.

ARKit is Apple's framework for AR apps and games. The SDK is specifically designed to take advantage of hardware capabilities of iOS devices, iPhone and iPad [10]. ARKit enables many AR functionalities such as location Anchor, scene geometry, people occlusion, motion capture, multiple face tracking, and collaborative sessions. *ARKit 4* adds a depth API, providing pixel-level depth information from LiDAR (Light Detection and Ranging) scanner on recent devices such as iPhone 12 Pro Max, and iPad Pro [11].

ARCore is an AR platform from Google enabling an AR experiences that seamlessly blends the digital and physical worlds[12]. The SDK provides APIs for all of the essential AR features like motion tracking, environmental understanding, and light estimation. ARCore is designed and created specially to take advantage of Android devices. It has plugins for Unity and Unreal Engine. The ARCore also supports creating AR sessions for iOS which enables shared AR experiences and adds features such as *cloud anchors*, uniquely identified locations in the environment that can make it possible to create multiplayer or collaborative AR experiences that can be shared even between supported platforms, and *augmented faces*, digital structures of automatically identified regions of detected faces of people in the environment, structures that can be used to overlay assets, such as textures and models, in a way that properly matches the contours and regions of an individual face.

Vuforia engine is a multi-platform AR software solution [13]. utilizing vision-based image recognition. It provides several features, enables capability of mobile apps and frees developers from technical limitations [14].

The Vuforia SDK supports a variety of 2D and 3D target types including marker-less image, 3D model, and a form of addressable fiducial marker, known as a *VuMark*. Additional features of the SDK include 6 DoF device localization, localized occlusion detection, runtime image target selection. The SDK allows to create and reconfigure target sets at runtime, meaning that image target can be created from a locally stored image file and added to an empty dataset to generate a trackable during the application runtime.

DOI 10.1109/CW52790.2021.00015

Vuforia supports a variety of operating systems such as iOS, Android, Windows, and devices including HoloLens 1 and 2, Magic Leap, Vuzix M300/M400, and RealWear HMT-1 and HMT-1Z1. With the *Vuforia Fusion* the SDK intends to solve the problem of fragmentation in AR-enabling technologies by providing an abstraction layer that makes use of other software frameworks available on the platform running the system, such as ARKit and ARCore, and fuse them with other Vuforia Engine features. Creating applications is free with Vuforia. However publishing an application requires a paid license.

WikiTude is a cross-platform SDK that helps to create immersive AR experiences [15]. It has a long list of features including object/scene tracking, instant tracking, image tracking, multiple image targets, cloud recognition, Geo AR, cylinder tracking, and multiple object tracking. WikiTude SDK has cross-platform support for Android, iOS, Windows and smart glasses. It can be used together with a wide range of programming languages and frameworks such as *JavaScript*, *Unity*, *Cordova*, *Xamarin*, *Flutter* and the native APIs of Android and iOS. The SDK allows to use CAD and other 3D models for 3D object model tracking. There is a free trial version of the SDK available, although a commercial SDK license is required to publish the work or to unlock all its features.

OpenXR, from the *Khronos Group*[16], is an attempt to reduce the fragmentation among hardware for AR and VR, and their accompanying software, by providing a single API connecting applications and various devices. Through OpenXR, developers can create applications, with engines and applications such as Unreal Engine and Unity, that work with any supported system, for example HoloLens 2 and Magic Leap.

AR.js is a lightweight framework for Web-based AR. The framework has features such as image tracking, location based AR and marker tracking [17]. The development team promises compatibility and high performance across all browsers that use *WebGL* and *WebRTC*. AR.js is an open source product using *JavaScript* based on *Three.js*, *A-Frame* and *jsartoolkit5* and no installations are required to take advantage of it.

WebXR, a W3C replacement of *WebVR* as API to support both AR and VR hardware specific features within a web-based application [18], is a working draft at the time of writing. It provides an interface for managing timing, scheduling and view, and other software are required for scene loading, model handling, etc. The support in web browsers is currently limited to Chrome and Edge (Desktop), Chrome Android and Samsung Internet (Mobile).

IV. Solutions for Optical See-through

For OST AR, we have found no less than six different head-sets that can, together with accompanying software, be considered complete solutions.

Microsoft HoloLens 2 is the second generation of the Microsoft's headworn OST AR[19]. The device has 54 degrees FoV (30 degrees on the first version) with a gradual transition on the edges to improve the sense of immersion. The virtual image projection has a resolution of 2K for each eye. The device comes with hand tracking and gesture detection system. HoloLens 2 is equipped with two 4 and 8 megapixels, visible light cameras, a one megapixel time-of-flight (ToF) depth sensor, and mixture of the accelerometer, gyroscope, magnetometer sensors. There are also two eye-tracking cameras inside the headset. The device comes with an internal computer running Windows Holographic (built on Windows platform), with a Qualcomm Snapdragon 850 coupled with 4 GB LPDDR4x RAM, 64 GB storage, Bluetooth and WiFi connections. The battery lasts for 2-3 hours and the device weighs 566 grams. There is also a hardhat implemented version for the industrial work environments.

The Unreal Engine (version 4.25 and above) has full-featured support for the HoloLens 2. The features include spatial mapping, hand/joint tracking, eye tracking, spatial anchors, camera access, voice input, UX tools, and support for Azure. The Microsoft Mixed Reality Toolkit (MRTK) for Unity is also available for developing AR software for the HoloLens 2. The toolkit provides a set of components and features, used to accelerate cross-platform AR app development in Unity[20]. The MRTK is based on the *OpenXR*III-B interface and its functionalities include object pose solver, UI control, in-editor simulation, hand tracking, speech recognition, work space boundary indication system, and the Spatial Awareness system which provides real-world environmental awareness in mixed reality applications.

There are a variety of example projects available to use with the MRTK. There is also the possibility to create AR applications with a direct line to the Windows Mixed Reality APIs with native app development using *OpenXR* or *legacy WinRT* for HoloLens 2. The Windows Mixed Reality API supports applications written in C++ and C#, allowing you to build your own framework or middleware in either language.

Epson Moverio BT-40 is a pair of eye-wear AR glasses that comes with Epson's 4th generation Si-OLED 1080p display/lens with a high contrast ratio of 500,000:1. There is a 0,45 inch wide panel with the aspect ratio of 16:9 and the FoV of 34 degrees for each eye. The BT-40 can be connected directly into devices such as smartphones, tablets, and laptops for being used as a secondary screen through its USB Type-C port. For tracking the device uses a 9 DoF motion sensor (gyroscope, accelerometer and magnetometer). The glasses uses the battery of the connected device. There is also an alternate model called *BT-40S* which include Epson's controller *BO-IC400*. The controller is a mini-PC running on Android operating system with a 2.95-inch touch enabled screen. The device has a 13 MP auto-focus camera, GPS, WiFi, Bluetooth, 64 GB of internal storage, and a MicroSD slot for up to 2 TB cards.

DOI 10.1109/CW52790.2021.00015

Figure 6. OST AR glasses; left: the Microsoft HoloLens 2. Right; the Epson Moverio BT-40 and the Epson Android base controller BO-IC400.

Developers can use the Moverio AR SDK along with Moverio glasses to detect and interact with real-world objects in their applications [21]. The SDK enables rendering digital content in 3D, using the real world as their canvas, by using the optical see-through capabilities. Some of the other features of the SDK include the Moverio-optimised calibration, 3D object tracking using CAD models, and 2D image tracking. There are Android API, Unity plugin, detailed documentation, and sample applications also available for the Moverio glasses.

Magic Leap 1 is a wearable computer for enterprise productivity [22]. As depicted in figure 7, the device has a headworn glasses form-factor and comes with a computing core called the LightPack and a controller. The device has two circular lenses that provide a FoV of 50 degrees horizontal and has two 1280x960 pixels screen, one for each eye, with a refresh rate of 120 Hz. Even though their front page specification does not include this information, it has been reported (for example [23]) that their patented multi-focal technology[24] is employed in the headset; a double set of waveguides allows rendering of virtual objects at two different focal distances, allowing unstrained AR view at both close interaction and longer distances. The device is capable of 6 DoF tracking and is equipped with a Full HD RGB camera, a depth IR camera, a 2x3-axis accelerometer, and a 3-axis magnetometer. The *LightPack* is equipped with NVIDIA's *Parker* SOC, 8 GB of RAM, and 128 GB of storage. For connectivity it uses Bluetooth 4.2 and WiFi. The *LightPack* provides up to 3 hours of battery life. There are also embedded stereo speakers and four microphones for spatial sound creation and voice commands. The *LightPack* weighs 316 grams. By the time of writing this paper an early access date is confirmed for the second version of the magic leap at Q4 2021. It is also confirmed that the *MagicLeap 2* will be half the size and about 20 percent lighter than the current version while doubling the FoV.

The Magic Leap operating system is called the *Lumin OS* and the software development kit is called *Lumin SDK* [25]. Magic Leap AR applications can be created using a variety of tools and platforms. Unity and Unreal Engines both include *Lumin OS* Build Support. There is also support for *MagicScript* which is a framework for developing native, mixed-reality apps with JavaScript. Web based Leap apps can be developed by the Lumin Web Platform. There are also APIs available for OpenGL and Vulkan. Some of the features of the SDK include world reconstruction, meshing, hand meshing, surface intersection, plane extraction, object detection, hand/eye tracking, and voice control.

Figure 7. OST AR glasses; left: *Magic leap 1* with the *LightPac* computing core and the controller. Right: the Epson Moverio BT-40 and the Epson Android base controller BO-IC400.

Glass Enterprise Edition 2 is Google's second edition wearable device which is intended to help businesses improve the quality of their output, and help their employees work smarter, faster and safer [26]. The device features a 640x360 pixel display and an 8 MP camera which is capable of recording Full HD videos. The Qualcomm Snapdragon XR1 SOC is coupled with 3 GB of RAM and 32 GB of storage as the processing unit placed inside the glasses. The connectivity is provided by Bluetooth 5.0 and WiFi. With its three near field beam-forming microphones and a mono speaker the device enables voice-activated assistance. It is given an IP rating of IP53, indicating a resistance to water spray and limited dust ingression. With its light weight of 46 grams (without frame) and up to 8 hours of battery life the device is designed to be wearable for longer periods.

The Google Glass 2 runs on Android, but it doesn't include Google Mobile Services (GMS) or Google Play services. The Android Studio and Android SDK can be used to develop AR applications. The Android SDK enables access to the various inputs and sensors available with the Google's device. Some of the features include detecting touch gestures on the trackpad, voice recognition, sensors' data, and barcode scanner. It is also possible to acquire some of the capabilities of the connected device such as keyboard, camera and GPS.

Vuzix M4000 is Vuzix's second-gen OST glasses [27] (See Figure 8, left). The device's single DLP display has 854x480 pixels resolution with diagonal 28 degrees FoV, up to 5000 nits of brightness, and contrast of 1000:1. It is equipped with a 4K 30 fps camera capable of taking 12.8 MP images. On the sensors side *M4000* has a 3-axis gyroscope, a 3-axis accelerometer, and 3 axis magnetometer. The device also has GPS and GLONASS. Controlling the device is enabled by a multi-finger 2-axis touch-pad and multi language voice detection. The Snapdragon XR1 Platform provides the processing power as the device's SOC coupled with 6 GB of RAM and 64 GB of storage. The connectivity is available via WiFi and Bluetooth 5.0. The device is given an IP67 rating therefore is capable to be used in physically demanding environments. The *M4000* can be equipped with an external

DOI 10.1109/CW52790.2021.00015

Figure 8. OST AR glasses: Vuzix M4000 with its extra accessories dark shades, battery pack and mountable hat (left), and Toshiba dynaEdge glasses with the dynaEdge DE-100 miniature PC (right).

Figure 9. Projective AR equipment from the *Lightform*; left: *LF2+*, A whole system including the projector for smaller scale installations. Right: *LFC KIT*, the system without a projector which can be set with any required projector.

battery which, depending on the size of the battery, can run between 2 to 12 hours. The long battery life and the device's light 100 grams weight makes it a good candidate for longer use-case scenarios. There are a bunch of accessories for the device such as helmet mounts, headband, hat Mount (with Vuzix Hat), power-bank, and Safety Glasses.

The M4000 runs on Android OS (currently Android 9) supporting its enhanced developer features and improved security for enterprise. Android Studio can be used to develop applications for the glasses taking advantage of the default API access such as voice recognition, camera, sensors, barcode engine, google cloud, and maps. The Vuzix speech recognizer is implemented as an Android service that runs locally on the device. The device also includes a barcode scanning engine that supports the most common symbologies. There are also a Unity Plugin and support for Wikitude (see section III-B) and Vuforia (see section III-B). The *Vuzix View* is a software developed by Vuzix to mirror and control the screen of the device to a Windows PC or Mac computer. The features include view and control, using keyboard navigating the device, take screenshots, save logs, and install APKs. The *Vuzix View* requires device to be connected to the computer.

Toshiba dynaEdge is a wearable hands-free AR solution designed to help large enterprises improve efficiency, quality and operating flexibility [28]. As depicted in Figure 8, right, the device comes as two key pieces: the headworn AR100 and the dynaEdge DE-100 miniature PC. The headworn part is fitted with a 0.26-inch screen of 640×360 pixels resolution, a 5 MP camera capturing Full HD videos at 30 fps, flash, speaker, and two microphones. The device utilizes a variety of sensors: proximity sensor, ambient light sensor, gyroscope, accelerometer, compass, and GPS. There are three buttons and a touch-pad for navigation control on the headworn device. The dynaEdge DE-100 is based on Intel Core m5/m7 SoC with 4—16 GB of RAM, and 128—512 GB of storage. Connectivity is enabled through WiFi and Bluetooth 4.2. The device has five navigation buttons, a microSD slot, and a fingerprint reader for security measures. The headworn part weighs 47 grams and the mini-PC, which also houses removable batteries, weighs 310 grams. An optional four-port battery charger enables the ability for continuous operation. The mounting accessories include: lens-less frame, safety frame, safety helmet mounts, and headband mount.

The dynaEdge runs on Windows 10 Pro and for the application developers the company offers Developer's Kits: *Dynabook Vision DE Suite* is Dynabook's proprietary software incorporating an easy-to-use approach. The software enables users to take photos, record and stream live video, save and retrieve documents, access diagrams, receive text messages and communicate through live video calls. *Dynabook Timer Pro* is a storyboard software allowing users to create detailed video-based training and support content using only Excel skills. The software requires no video editing and content creators can add audio, text, graphics and hyperlinks to the Storyboard directly in the Microsoft Excel.

V. Solutions for Spatial AR

It is apparent that both VST and OST are much more popular technologies at the moment. Only one device specifically designed for projected AR that could be found by the time of writing this paper.

Lightform LF2+ [29] is equipped with a Full HD, 1000 lumen LED projector along with a 5 MP camera and an IR camera array for tracking, see Figure 9 (left). The device has an integrated computer with network connectivity. According to the manufacturer the device is recommended for small scale installations and indoor spaces. Another solution from *Lightform* is the *LFC Kit*, see Figure 9 (right), which does not constitute a complete solution, since it requires an external projector. This, however, allows the buyer to choose projector separately, base on the project requirements and potentially allowing for larger scale installations.

Both *LF2+* and *LFC Kit* come with a free version of the Lightform's *Creator* software.

Creator is a content creation software optimized for use with the LF2+ AR projector. The software features projection mapping, pairing process, sound reactive effects, and scan based smart selection. The Creator has an easy to use interface while providing a large database of built-in effects and stock videos and animations available for AR projects.

Similar to our earlier discussion about tablets and phones being a potential AR device, any off-the-shelf projector also can be used to create projection AR. However, without a

DOI 10.1109/CW52790.2021.00015

proper tracking system and AR software we cannot call it an AR solution product.

VI. Discussion

There is a large number of devices, with various hardware and software technologies, available today which can be used to provide AR. Choosing among these devices mostly relates to the specifics of the intended AR project. For projects requiring a shared AR experience, SAR can be a suitable approach. As discussed in Section V, the Lightform's *LF2+* works better for a smaller scale environments of about 3.5 meters wide while the *LFC KIT* coupled with a capable projector can be used for larger scale environments such as exhibitions.

Handheld VST AR is the most common used AR technique due to the availability of capable phones and tablets and thus no need for expensive equipment. There are multiple software solutions available for handheld AR that can be chosen from based on target device and software development skills. A major drawback of using handheld AR is the need to hold the device by hand (both hands for larger devices) which reduces the ability of using hand interaction. This, in practice, also may lead to hand fatigue in cases requiring longer use.

The OST AR devices usually come in the head mounted form-factor which frees up the user's hands. In Section IV we went through a number of the most capable OST AR devices and their software solutions. An overview of the specifications is listed in Table I. Overall, we found Microsoft HoloLens 2 to be a capable device in regards to the 3D mapping and visualization of the AR content. The device also enables the virtual world interaction with its hand tracking capabilities. However, using the HoloLens 2 for a longer period of time may be problematic due to its rather high weight and short battery life. The Magic Leap weighs around half of the HoloLens 2 and provides a wand, a 6 DoF tracked controller common in VR, for interaction although it provides only three hours of battery life. The Vuzix M4000 is a good candidate for long use scenarios. The frame weighs only 100 grams and it can provide up to 12 hours of continued battery life when connected to its power bank accessory. Having an IP76 rating makes it also capable to be used in more demanding environments. Among the reviewed devices Toshiba dynaEdge is the only device capable of working continuously while it is plugged to the power source. However, both the M4000 and the dynaEdge only have a display for one eye which can affect the amount of immersion in AR.

Because of their underlying principles leading to different optical effects, these displays are differently suited for different aspects in the MR spectrum. In particular, all display systems incapable of hiding the real world, thus both SAR solutions and currently also all commercially available OST AR solutions, are limited to the AR side of the spectrum. Some manufacturers may market their systems as Mixed Reality displays, but this is then actually a misnomer, since they do not support Augmented Virtuality (AV).

VII. Conclusions

In this paper we have provided a comprehensive list of currently available complete solutions for Augmented Reality, categorised into Video See-through AR, Optical See-through AR and Spatial AR, and with a review of their individual features and properties. Temporarily disregarding the difference in display properties, we can conclude that the OST approach is the currently most popular when it comes to specialized display hardware, but also that even more software solutions for the VST AR approach are available, typically for running on mobile devices. Hardware solutions for both VST AR and SAR can be considered least common. However, it is worth noting that it is just recently that any complete solution for SAR has become commercially available and we are eagerly following the development of this market segment.

Acknowledgements

This work was supported by Visual Sweden through the Augmented Operator project (VS2006-E). Visual Sweden is funded by Vinnova Vinnväx grant 2019-02261. Support was also provided by SSF grant RIT15-0097: *SymbiKBot: Robot-Assisted Hastily Formed Knowledge Networks*.

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DOI 10.1109/CW52790.2021.00015

Table I
SUMMERY OF DEVICE SPECIFICATIONS FOR THE OPTICAL SEE-THROUGH DEVICES.

Device	HoloLens 2	BT-40(S)	Leap 1	Glass 2	M4000	dynaEdge
Manufacturer	Microsoft	Epson	MagicLeap	Google	Vuzix	Toshiba
Screen	2048×1080 x2 120 Hz -	1920x1080 0.45″ x2 OLED 60 Hz	1280x960 x1 16.8 M C 120 Hz	640x360 x1 - -	854x480 x1 5000 nits OLED	640×360 0.26″ x1 -
FoV	54° -	34° Diag	50° Horiz	- -	28° Diag	- -
SOC Brand Placement	850 SD Internal	SXR1130 QC External	Parker Nvidia External	XR1 SD Internal	XR1 SD Internal	Core m7 Intel External
RAM (GB)	4	4	8	3	6	4–16
Storage (GB)	64	64	128	32	64	128–512
Still Video EyeTracking Depth	8 MP-4 MP FHD@30 IR x2 1 MP ToF	x x x x	2 MP FHD@30 IR x	8 MP FHD@30 Blink x	12.8 MP 4K@30 x x	5 MP FHD@30 x x
Accelerometer Gyroscope Magnetometer	✓ ✓ ✓	✓ ✓ ✓	✓x2 x ✓	✓ ✓ ✓	✓ ✓ ✓	✓ ✓ ✓
Other Sensors	- -	Motion Light	- Light	- -	GPS GLONASS	GPS Light
Control Voice	Hand ✓	Controller ✓	Controller ✓	Touch ✓	Touch ✓	Controller ✓
Wi-Fi Bluetooth	✓ 5	✓ 5	✓ 4.2	✓ 5	✓ 5	✓ 4.1
IP Rating	x	IPX2	x	IP53	IP76	x
Weight (g)	566	170	316	46	100	47+310
Battery (Hours)	2—3 -	1.5–4 Extend	3 -	8 800 mAh	2–12 Extend	Removable Plug

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DOI 10.1109/CW52790.2021.00015