Merging real and virtual worlds: An analysis of the state of the art and practical evaluation of Microsoft Hololens

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Achieving a symbiotic blending between reality and virtuality is a dream that has been lying in the minds of many people for a long time. Advances in various domains constantly bring us closer to making that dream come true. Augmented reality as well as virtual reality are in fact trending terms and are expected to further progress in the years to come.

This master’s thesis aims to explore these areas and starts by defining necessary terms such as augmented reality (AR) or virtual reality (VR). Usual taxonomies to classify and compare the corresponding experiences are then discussed.

In order to enable those applications, many technical challenges need to be tackled, such as accurate motion tracking with 6 degrees of freedom (positional and rotational), that is necessary for compelling experiences and to prevent user sickness. Additionally, augmented reality experiences typically rely on image processing to position the superimposed content. To do so, “paper” markers or features extracted from the environment are often employed. Both sets of techniques are explored and common solutions and algorithms are presented.

After investigating those technical aspects, I carry out an objective comparison of the existing state-of-the-art and state-of-the-practice in those domains, and I discuss present and potential applications in these areas. As a practical validation, I present the results of an application that I have developed using Microsoft HoloLens, one of the more advanced affordable technologies for augmented reality that is available today. Based on the experience and lessons learned during this development, I discuss the limitations of current technologies and present some avenues of future research.

Keywords: augmented reality, virtual reality, mixed reality, Microsoft Hololens, human-computer interaction, computer vision
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# List of Abbreviations

| Abbreviation | Meaning                                                      | Defined in: |
|--------------|--------------------------------------------------------------|-------------|
| AEC          | Architecture Engineering and Construction                   | section 4.2 |
| AR           | Augmented Reality                                           | section 2.1 |
| ASIC         | Application-Specific Integrated Circuits                    | section 7.2 |
| AV           | Augmented Virtuality                                        | section 2.2 |
| BCI          | Brain-Computer Interfaces                                   | section 7.3 |
| BRIEF        | Binary Robust Independent Elementary Features               | section 3.2.2|
| BRISK        | Binary Robust Invariant Scalable Keypoints                  | section 3.2.2|
| CAAD         | Computer-Aided Architectural Design                         | section 4.2 |
| CAD          | Computer-Aided Design                                       | section 4.2 |
| CAVE         | Cave Automatic Virtual Environment                           | section 2.3 |
| DoF          | Degrees of Freedom                                          | section 3.1 |
| DoG          | Difference of Gaussians                                      | section 3.2.2|
| DSP          | Digital Signal Processor                                    | section 7.2 |
| EEG          | Electroencephalograms                                       | section 7.3 |
| EKF          | Extended Kalman Filter                                      | section 3.3 |
| EMG          | Electromyograms                                             | section 7.3 |
| EPM          | Extent of Presence Metaphor                                 | section 2.5 |
| EWK          | Extent of World Knowledge                                   | section 2.5 |
| FAST         | Features from Accelerated Segment Test                      | section 3.2.2|
| FLANN        | Fast Library for Approximate Nearest Neighbors              | section 3.2.2|
| FoV          | Field of View                                               | section 2.1 |
| FREAK        | Fast Retina Keypoints                                       | section 3.2.2|
| HMD          | Head Mounted Display                                        | section 2.1 |
| HPU          | Holographic Processing Unit                                 | section 6.1.1|
| IMU          | Inertial Measurement Unit                                  | section 3.1.4|
| LoG          | Laplacian of Gaussian                                       | section 3.2.2|
| MR           | Mixed Reality                                               | section 2.4 |
| ORB          | Oriented Fast Rotated Brief                                 | section 3.2.2|
| PTSD         | Post-Traumatic Stress Disorder                              | section 4.1 |
| RF           | Reproduction Fidelity                                       | section 2.5 |
| RGB          | Red Green Blue                                              | section 6.3.3|
| RPD          | Retinal Projection Display                                  | section 2.1 |
| RSD          | Retinal Scanning Display                                    | section 2.1 |
| RTT          | Round-Trip Time                                             | section 6.3.3|
| RV           | Reality-Virtuality (continuum)                              | section 2.4 |
| SAR          | Spatial AR                                                  | section 2.1 |
| SIFT         | Scale-Invariant Feature Transform                            | section 3.2.2|
| SLAM         | Simultaneous Localization And Mapping                       | section 3.3 |
| Acronym | Description | Section |
|---------|-------------|---------|
| SMB     | Small and Medium size Business | 5.2     |
| SURF    | Speeded Up Robust Features | 3.2.2   |
|ToF      | Time of Flight | 3.1.3   |
| UI      | User Interface | 7.3     |
| UWP     | Universal Windows Platform | 6.3.3   |
| VPU     | Vision Processing Unit | 7.2     |
| VR      | Virtual Reality | 2.3     |
| VRD     | Virtual Retinal Display | 2.1     |
| VRET    | VR Exposure Therapy | 4.1     |
Chapter 1

Introduction

Merging real and virtual worlds has been in many people’s minds for decades but, as the hardware evolved (in terms of computing power and display quality) and because of advances in computer vision, such experiences are more believable every day.

While science fiction cinematographic works have helped us envision what the future could be, with futuristic virtual interfaces in movies such as Minority Report (2002) and Iron Man (2008), the aforementioned improvements make them realistic.

The huge success of Pokémon Go as well as financial forecasts make us believe in the potential of augmented and virtual reality in many domains of human endeavor. The exact meaning of those terms will be explained in chapter and potential applications will be discussed in later chapters.

This master’s thesis will first define, classify and compare categories of reality/virtuality experiences. Then, chapter will discuss several of those with regards to the techniques and technologies that are required to enable the corresponding experiences. Each classification will be illustrated with concrete applications (in chapters and ). Chapter will then present a project created as part of this master’s thesis and that runs on Microsoft Hololens.

Finally, based on the experience acquired and the state of the art, chapter will discuss current limitations as well as future prospects and research in those areas.

1 http://www.pokemongo.com
Chapter 2

Definitions and taxonomy

Lots of papers, studies, blog articles and other resources can be found about different ways of merging reality and virtuality. Most people have heard about several terms such as augmented reality and virtual reality but what do they really mean? How do they compare/differ? This first chapter will define those terms and discuss taxonomies to understand how they relate.

2.1 Augmented Reality (AR)

Augmented Reality (which will from now on be referred to as AR) describes the blending of the real world with a virtual one. It can basically be seen as "adding virtual things on top of the real world’s perception". A typical example of an AR device is Google Glass [58] whereas the game Pokémon Go [111] helped popularize AR with its integration of Pokémon on top of the live camera feed as if they were there in the real world (as shown on figure 2.1).

![AR feature in Pokémon Go](http://img.phonandroid.com/2016/07/pokemon-go-capture.jpg)

In order to enable AR experiences, different kinds of displays can be used. The following sections will introduce a few of those categories and provide concrete examples.
Monitor-based AR displays

This is the simplest type of AR displays available. It refers to non-immersive experiences where the augmentation happens on a "distant" screen, such as a TV or a smartphone (even though in that particular case, the more specific "handheld AR" is often used). The display is treated as a window to the augmented world (hence the alternative name "Window-on-the-World" given by Milgram et al. [104]) created from live or stored video images. Due to its accessibility (from the user’s point of view) it is the most prominent form of AR experiences, with lots of applications in sports broadcasting (examples shown in figures 2.2a and 2.2b). The previously mentioned feature in Pokémon Go also is an example of monitor-based AR as it takes place on smartphone screens.

See-through AR displays

A second class of displays used for AR experiences allows the user to see the augmented world "directly" in the sense that he sees the real world from his own perspective (as opposed to monitor-based displays that show images from a "distant" camera). Figure 2.3 pictures some possibilities to make the augmentation happen and highlight differences in where the observer is located in relation to the real object as well as what type of image is generated (i.e. planar or curved).

Head-mounted displays (HMDs) are often linked to Virtual Reality but are also extensively used in AR. In the context of a video see-through HMD, the user sees the real world through a camera system attached to the device that aims to reproduce the effective viewpoint of the user’s eyes. It is also possible to project virtual elements on a transparent surface in front of the observer. In that case, the display is referred to as optical see-through. Depending on where that surface is located in relation to the user, different names are given: spatial see-through display if it is separated from the user’s
2.1. Augmented Reality (AR)

Figure 2.3: Different ways of generating AR images [12]

head; or simply optical see-through HMD if it is attached to it. A current example of a device falling into the latter category is Microsoft Hololens. Even though that device will be further discussed in chapter 6, figure 2.4 shows the idea behind it: anchoring holograms into the real world.

Figure 2.4: Microsoft Hololens use case: Designing operating rooms with holograms integrated into the real world.

It is worth mentioning that different issues arise depending on the type of see-through being used, as pointed out by Fuchs and Ackerman [46]. An optical see-through HMD will provide an unmatched direct view of the real world but will require more advanced technologies (e.g., to accommodate changes in head position/orientation rapidly enough, to deal with light intensity and to properly handle occlusion). On the other hand, a video see-through HMD will have to make sure the field of view (FOV, the extent of the scene that can be seen, generally measured in degrees) is acceptable and,
more importantly, that the video itself has a high and stable framerate. Indeed, whereas a video see-through display can make sure the real world and its augmentations are synchronized, it might introduce a delay between the movements of the user’s head and what he sees. This has to be handled with caution as, otherwise, users might suffer from nausea. Another element worth pointing out is the perhaps surprising "age" of see-through displays. In fact, it appears that HMD systems were developed as early as in the late 1960s, by Sutherland [155] and, at the same time, by Furness [49] for the US Air Force with projects that then lead to the "Super Cockpit" program [50, 157] in 1986.

The last kinds of see-through displays that will be discussed here are retinal displays (sometimes named RPDs for Retinal Projection Displays, RSDs for Retinal Scanning Displays or even VRDs for Virtual Retinal Displays). As shown on the top-left corner of figure 2.3, it is possible to generate AR images closer to the eye. In fact, retinal displays are drawing those images directly onto the eye’s retina using low-power laser beams. While the principle could frighten readers at first glance, it should be mentioned that the eyes of the wearer remain safe, even after being exposed for several hours [74]. Even better, the technology doesn’t tire the eyes as much as a conventional HMD [94]. Several prototypes (e.g. by Schowengerdt et al. from the University of Washington [144]) and even actual products (e.g. Laser EyeWear (LEW) [74] from Fujitsu, QD Laser and the University of Tokyo) exist but are not available as of yet. Despite the fact that it is not directly related to AR, it is interesting to note that such a technology can also be used to help people with low vision that "standard" glasses cannot correct [37].

Spatial AR

Sometimes referred to as projection or projective AR, spatial AR (SAR) is about augmenting reality by projecting images directly onto real objects. Although figure 2.3 already mentioned "spatial" and "projector", SAR did not really belong in the see-through category as there is no actual display other than the real world objects themselves. First introduced by Raskar et al. [122], SAR can therefore "naturally" provide multi-user experiences. As of now, most applications of those techniques are related to a cultural context where images are projected onto surfaces such as the facade of a building. Sometimes referred to as monumental projections [72] and video or 3D mapping, those techniques can also provide 360°experiences [107] as well as user’s interaction [69].

Other types of AR

So far only visual AR categories have been presented. It should however be mentioned that other kinds of AR exist that are using different senses: audio, haptic, olfactory and gustatory AR. Haptic (touch) interfaces will briefly be discussed in chapter 7 but audio, olfactory and gustatory AR go beyond the scope of this work.
2.2 Augmented Virtuality (AV)

While AR was about augmenting the real world with virtual objects, augmented virtuality (AV) is about adding real world elements into a virtual world. Most AV applications can be subsumed as “chroma key experiences”. Examples include weather forecast broadcasts and video conferences into virtual environments \[125\] (as shown in figure 2.5). Even closer to virtual reality (discussed in section 2.3), applications where the user’s hands are integrated into a virtual world (e.g. a “virtual studio for architectural exploration” by Bruder et al. \[19\]) are also examples of AV.

![Figure 2.5: cAR/PE!: AV videoconferencing system by Re-genbrecht et al. \[125\]](http://i.amz.mshcdn.com/auQDd-I-BKnVdiXWK7r53vtDA_g=/fit-in/1200x9600/2014%2F04%2F04%2F03%2FEyephoneVPL.99ebb.jpg)

As of now, AV is nowhere near as popular as AR or VR. In fact, it is highly unlikely that this situation will change in the future for two reasons. Firstly, because the boundaries between those categories can be "blurred" and people will naturally use terms they know. Secondly, because technologies will keep on improving and it will become harder and harder to distinguish what is physically real from what was virtually added.

2.3 Virtual Reality (VR)

Virtual Reality (VR) describes experiences where the user is entirely immersed into a three-dimensional virtual world and interacts with it. While the paternity of the concept is unclear, VR as a term is generally attributed to Lanier who worked actively \[31\] \[87\] in the domain in the late 1980’s. The usual equipment used for VR experiences involves a HMD and some kind of controller (in early products from Lanier: a glove). Figure 2.6 shows one of the first VR commercial products by VPL Research (Lanier’s company) in 1989.
It should however be mentioned that VR is not limited to HMDs. In the early 1990’s, Cruz-Neira et al. at the University of Illinois developed CAVE (Cave Automatic Virtual Environment) [33], a VR setup in a cubic room, with images projected on the walls. This alternative to HMDs provides great immersive experiences with a wide field-of-view (see figure 2.7) but requires extra room and isn’t as affordable.

2.4 The Reality-Virtuality continuum

Now that some terms have been defined, it is time to introduce the most frequently used taxonomy: the Reality Virtuality continuum by Milgram et al. [105]. In 1994, AR was already a popular term in the literature but different definitions where given. Therefore, Milgram et al. wanted to clarify what that term meant and how it related to VR. In order to do so, they created a continuum (shown in figure 2.8) that is still considered as the main reference to classify experiences mixing real and virtual elements.
2.4. The Reality-Virtuality continuum

The idea behind this one-dimensional taxonomy is that there is a broad range of applications between an entirely real world and a solely virtual environment. They can be placed on that axis depending on whether they are primarily using reality or the virtual world.

In that figure, the term Mixed Reality (MR) is introduced but we (purposely) did not define it yet. In fact, it has been misused in recent years to describe "spatial aware" AR devices and experiences (further discussion on that in chapter 6). Milgram et al. defines a MR environment as “one in which real world and virtual world objects are presented together within a single display, that is, anywhere between the extrema of the RV continuum”. Therefore, MR is a subset containing AR, AV and even VR experiences as they are not entirely virtual because section 2.3 stated that, in order to be considered as a VR experience, an application needs to include user interactions.

In his PhD thesis about spatial AR, Ridel [129] proposed an extended version of Milgram et al.’s RV continuum to differentiate SAR from see-through AR. As SAR directly projects the images on a real world surface, he chose to put it further the left. Figure 2.9 shows that version of the continuum.

In order to clarify where VR experiences should be placed on that continuum, we slightly modified Ridel’s version. The resulting further extended RV continuum is shown in figure 2.10.

Even though some terms mentioned previously are not included in it (e.g. we could also differentiate between different kinds of see-through AR), we believe this version is sufficiently complete to clarify everything that has been mentioned so far.
Chapter 2. Definitions and taxonomy

2.5 Other taxonomies

As a one-dimensional continuum is not sufficient to highlight the differences between a plethora of mixed reality experiences, other taxonomies are needed. In fact, in the same paper [104], Milgram et al. summarize the main points of a three-dimensional taxonomy for mixed reality systems, that is further discussed in another paper [103]. The paper describes 3 axes: Extent of World Knowledge (EWK: how much do we know about the - real or virtual - world in which the experience happens?), Reproduction Fidelity (RF: is the augmented content realistic?) and Extent of Presence Metaphor (EPM: is the user immersed in the experience or does he look at a monitor?). The resulting three-dimensional "hyperspace" is depicted in figure 2.11.

Another classification worth mentioning is Fuchs’ VR taxonomy [48] based on what he describes as its inherent functions: the ability for the user to pull himself out of his own real environment (1) and/or his present time (2) in order to interact (3) in a virtual world.

(1) leads to states where the user is:

\[
\begin{cases}
L_\rightarrow & \text{in a distant or non-human scale environment} \\
L_U & \text{in a virtual world with other users} \\
L_0 & \text{in the same place or the location is irrelevant to the application}
\end{cases}
\]
2.5. Other taxonomies

(2) leads to states where the user is: \( T_0 \) in present time
\( T_- \) in the past
\( T_+ \) in the future

(3) leads to states where the user is: \( IA_r \) in a world that simulates reality
\( IA_i \) in an imaginary/symbolic world
\( IA_0 \) in the real world

Experiences can then be classified by combining those characteristics (14 resulting categories because multiple users (\( L_0 \)) can only interact in the present moment (\( L_0 \))). Virtual tours are therefore in (\( IA_r, T_0, L_0 \)) and a VR sci-fi game would be in (\( IA_i, T_+, (L_0 + L_-) \)), with the + sign meaning "and/or".

Many other taxonomies have been proposed. A few more examples are classifications based on what is being augmented \([29, 66]\) (user, objects or environment), by purpose \([38]\), or based on whether the action is determined by the system or the user \([127]\). However, Milgram et al.’s RV continuum remains the standard reference in the domain and will therefore be used throughout this thesis.
Chapter 3

Motion tracking and related computer vision techniques

VR and AR have shared requirements in terms of motion and positional tracking, common techniques to meet those needs will therefore be presented. Additionally, AR applications often have to recognize landmarks in the environment and get a sense of the user’s surroundings, the corresponding problems and specific computer vision techniques to tackle them will also be discussed in this chapter.

3.1 Motion tracking

In order to enable compelling VR applications, a way to track the user’s head (and optionally some kind of controller) is needed. This section will present a few techniques that can be used for that matter but first, let us clarify what we need exactly.

We want to be able to track movements in 3D space, which means we need to know the tracked object’s position as well as its rotation. That kind of tracking is usually labeled as 6 DoF (degrees of freedom) because the object effectively has 6 separate ways to modify its position (3 axes: x, y, z) and rotations (yaw, pitch, roll) as seen in figure 3.1, where each color represents one of those degrees of freedom.

![Figure 3.1: 6 degrees of freedom (DoF)](image)
An ideal tracking system would need to meet the following characteristics:

- High accuracy: user motions should be accurately tracked
- High precision: jitter should be negligible and imperceptible by the user, no movement should be registered when the tracking target is not moving
- Low latency and high update rate: the delay between a motion and the system’s awareness of that motion should be very low as failing to do so leads to user sickness
- Wide range: users should not be restricted to a small area of interaction around the sensor(s)
- High mobility: users should be able to move freely (wireless and autonomous trackers are therefore preferred) in their environment which also implies the tracking system has to be as small and light as possible
- Environmental robustness: disruptive elements from the environment (e.g. sunlight, temperature or magnetic fields) should not alter the tracking system’s quality

### 3.1.1 Mechanical tracking

Mechanical tracking probably is simpler than other methods, at least conceptually. In fact, the tracked object is typically directly linked to the system via several mechanical "arms" (made up of articulated pieces). The object’s position and rotation is then determined using the angles of the arms’ joints (with sensors placed on those joints). The same principle (calculating the angles of specific joints) has also been used for full body tracking with complete suits (that are very expensive but typically wireless) such as Inition’s MotionShadow\(^2\) pictured in figure 3.2.

The issue with that solution therefore is either the cost (for body suits) or the restricted movements provided by mechanical structures the user is attached to.

### 3.1.2 Magnetic tracking

Magnetic tracking uses a base station that generates current and therefore a magnetic field. Sensors are placed on the tracked device and are able to measure the magnitude of that magnetic field (it varies depending on the distance) as well as its direction (an example of a magnetic field can be seen in figure 3.3).

1. [https://upload.wikimedia.org/wikipedia/commons/f/fa/6DOF_en.jpg](https://upload.wikimedia.org/wikipedia/commons/f/fa/6DOF_en.jpg)
2. [https://www.inition.co.uk/product/motionshadow-full-body-tracking-system/](https://www.inition.co.uk/product/motionshadow-full-body-tracking-system/)
3. [https://www.inition.co.uk/wp-content/uploads/2014/11/Shadow_full-body-519x415.jpg](https://www.inition.co.uk/wp-content/uploads/2014/11/Shadow_full-body-519x415.jpg)
3.1. Motion tracking

Using that data, both the position and the rotation of the device can be determined. Example of commercial products using that technology include Razer Hydra controllers[^4] (now classified as "legacy") and Polhemus trackers[^5].

[^4]: http://www.razersupport.com/gaming-controllers/razer-hydra/
[^5]: http://polhemus.com/applications/electromagnetics
[^6]: http://www.allegromicro.com/~media/images/Design/Position-And-Level-Sensing-Using-Hall-Effect-Sensing-Technology/fig9.ashx?w=450&h=438&as=1&la=en&hash=D2BFDB36804067CF413236AFC931D8DBBCCE12D

That solution means that the base station does not need to be in sight (with regards to the sensors) but other devices (electrical appliances, computers, etc) can cause disturbances.

3.1.3 Acoustic tracking

Another possibility to track those 6 DoF uses ultrasonic (> 20000 Hz) signals emitted by several sources. Receivers are placed on the tracked object and...
Time of Flight (ToF) measurements determine the distance from the emitter to each receiver. As the sensors’ geometry on the tracked object is known, the position and rotation can be computed. Even though it isn’t the most popular method in VR, a few commercial products exist such as some InterSense trackers[^7].

That solution is cheap but isn’t very resistant to environmental interference (e.g. pressure or temperature changes).

### 3.1.4 Inertial tracking

Using accelerometers and gyroscopes (inertial sensors as they are based on the principle of inertia i.e. $F = ma = m \frac{dv}{dt}$), one can also get a 6-DoF tracking solution. An accelerometer measures the difference between the object’s acceleration projected on the sensitive axis and gravity (9.81 m/s$^2$ upwards), thus enabling one-dimensional position tracking, whereas gyroscopes measures rotation around a single axis. Resulting measurements (from 3 accelerometers and 3 gyroscopes) can then be used to provide both the position and the rotation of an object, in what is generally called an IMU (inertial measurement unit).

That solution is very widely available as smartphones contain those sensors, most people therefore have a 6 DoF tracking system in their pocket (although only rotation data is relatively reliable, because of the drifting problem described below). Other products using those principles include Nintendo’s Wiimote (that also uses optical tracking, discussed in section 3.1.5) pictured in figure 3.4 as well as Microsoft Hololens (see section 6.1).

![Figure 3.4: Nintendo’s controller, the Wiimote](https://vignette4.wikia.nocookie.net/ssb/images/0/0c/WiiMote.jpg/revision/latest?cb=20070925042013)

The biggest advantage of using inertial tracking is that it doesn’t require any base station or emitter but one should note that it also is immune to

[^7]: [http://www.intersense.com/](http://www.intersense.com/)
[^8]: [https://vignette4.wikia.nocookie.net/ssb/images/0/0c/WiiMote.jpg/revision/latest?cb=20070925042013]
environmental interference. However, they are either very expensive (compared to other solutions) or less accurate. They are often coupled with another method because accelerometers cannot be used for long-term tracking on their own (as demonstrated in [83]). They in fact drift and because accelerometers measure acceleration, from which a relative position is derived, offset errors are accumulated quadratically.

3.1.5 Optical tracking

Optical solutions are probably the most diverse and widely used tracking systems. The general principle is that some kind of sensor (typically some kind of camera) will either track features/patterns in the environment or active/passive markers and use them to determine the object’s position and rotation. The camera(s) can either be “external” to the tracked object (outside-in tracking) or attached to it (inside-out tracking).

Active and passive markers

Solutions using active markers rely on light-emitting sources such as LEDs or simple light bulbs that are placed on the tracked object. Those lights are often invisible to humans (infrared lights that are only visible to infrared sensors) but need a power source. Depending on how and what one needs to track, the need for batteries can be an issue.

![Figure 3.5: Active markers on the Oculus Rift DK2](http://3dvision-blog.com/wp-content/uploads/2014/09/oculus-rift-development-kit-2-ir-markers.jpg)

Passive markers are not luminescent themselves but often reflect light emitted by a source. The light emitted and its reflection typically are invisible to the human eye as well. “Paper” markers can be used as well and are classified as passive markers.

As previously mentioned, it is also possible to dispose of markers entirely e.g. using features from the environment or a projected pattern.
Invisible light

Using light sources typically leads to better results but it is generally desirable not to distract the user with them. Infrared lights are "too red" for the human eye to see them and are therefore often used as "invisible" lights. It should however be mentioned that using several infrared sensors can be a problem (e.g. overlapping projected patterns confusing the sensors) and that there still are drawbacks (e.g. sunlight interferences and issues with certain types of surfaces). A few examples of techniques using infrared lights are given below.

The first version of Microsoft’s Kinect camera uses a technique called "structured light", which essentially projects infrared patterns to get depth information. With that data, it can compute a 3D representation of the scene it sees. Figure 3.6 shows the principle behind the method: the projected pattern will be distorted according to its distance from the source. A more detailed explanation using animations can be found in [158].

![Structured Light Principle](http://imagebank.osa.org/getImage.xqy?img=QC5sYXJnZSxhb3AtMy0yLTEyOC1nMDAx)

**Figure 3.6:** The structured light principle used in Kinect v1

Released in late 2013, the second generation, "Kinect for Xbox One" also known as Kinect v2, employs a lightly different technology to get depth data: the time of flight (ToF) measurements we talked about in section 3.1.3. The light emitted by the sensor is reflected on many kinds of surfaces and the time it takes to return to the sensor is measured. As light speed is a well known and constant value, the distance from the sensor can be computed. The principle is shown in figure 3.7, where one can see that time is in fact measured using phase shifts.

Another popular example of an optical tracking system is Valve’s Light-house with its base station(s), often paired with HTC Vive’s headset and controllers. A high-level view of how the optical tracking works can be found in [164] and Kreylos’s article [82] provides a lot more details as well as precision and accuracy evaluations.

Each base station uses two lasers to project lines of light (one laser horizontally; the other one vertically, with regards to the station’s coordinate system). As only one laser can emit light at any time, the base stations are

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10 http://imagebank.osa.org/getImage.xqy?img=QC5sYXJnZSxhb3AtMy0yLTEyOC1nMDAx
11 https://hsto.org/getpro/haBr/post_images/0e070ce/ff6/0e00ceff672a747577bb86fbd031242e.png
3.1. Motion tracking

Figure 3.7: The ToF continuous wave technology used in Kinect v2.

synchronized using flashing LEDs. The same flashing LEDs are used to synchronize tracked devices.

The idea (pictured in figure 3.8) is that when it receives a synchronization pulse, a receptor starts counting. When a laser beam hits a sensor, the counting stops and the object’s position is updated (on a single axis as lines of lights are either horizontal or vertical). In between those “optical updates”, an IMU is used to estimate the object’s position (one of Lighthouse’s purposes is therefore to correct the IMU’s inevitable drifting).

Figure 3.8: Valve’s Lighthouse illustrated with an HTC Vive headset and controllers.

3.1.6 Hybrid solutions

As Welch and Foxlin imply in their paper’s title (“Motion tracking: no silver bullet, but a respectable arsenal” [160]) and as seen in previous sections, every method has its drawbacks. For that reason, lots of trackers are combining different technologies in hybrid solutions. The term “sensor fusion” is often coined to refer to combining sensory data. In order to blend that data, several algorithms can come to help. A very frequent choice is Kalman filtering (originally described in 1960 [76]) that relies on a mathematical model to filter signals with an acceptable amount of statistical noise and inaccuracies.

https://i.ytimg.com/vi/J54dotTt7k0/maxresdefault.jpg
Chapter 3. Motion tracking and related computer vision techniques

One should be aware that, sometimes, hybrid trackers are described as \( n \)-DoF solutions, with \( n > 6 \). As there only exist 6 degrees of freedom for rigid bodies, this is simply a marketing trick to indicate that different sensors are tracking the same degrees of freedom. For example, IMUs are frequently equipped with magnetometers in addition to the accelerometers and gyroscopes. Those magnetometers can be used as compasses to "reset" gyroscopes’ drift. As each type of sensor (3-axis accelerometer, 3-axis gyroscope and 3-axis magnetometer) measures 3 degrees of freedom, the device is occasionally labeled as a 9-DoF tracking system (when in fact gyroscopes and magnetometers are measuring the same degrees of freedom).

3.2 Vision-based tracking

The set of techniques discussed in section 3.1 and their combination are sufficient for VR and motion capture. However, AR applications typically rely on image processing and often use "paper" markers (they can be used for motion tracking but other techniques are generally preferred) or features detected in the environment. While vision-based tracking is a form of optical tracking and could therefore be placed in section 3.1.5, the variety of techniques in use and their predominance in AR deserve a specific section.

3.2.1 Template markers

Traditional vision-based tracking uses template markers, generally square patterns as they are believed to be the best choice to position augmented content, with regards to the criteria chosen in [115] by Owen, Xiao, and Middlin. A few examples of well-known square markers are shown in figure 3.9.

![Figure 3.9: Some well-known square patterns](https://artoolkit.org)

ARToolkit\(^\text{13}\) probably is the most popular open-source AR tool. Figure 3.10 helps explaining how the system works.

\(^\text{13}\) https://artoolkit.org
3.2. Vision-based tracking

It first searches for black square shapes. Once one has been found, its inner content is analyzed. If that embedded content matches an expected pattern (the exact marker has thus been identified), the corresponding content is superimposed on it (with proper scale, position and orientation by using the marker’s corners).

![ARToolkit’s work-flow to superimpose augmented content on traditional template square markers](https://artoolkit.org/documentation/lib/exe/detail.php?id=3_Marker_Training%3Amarker_about&media=diagram.jpg)

Different kinds of markers have been utilized with interesting properties for some use cases. For example, a QR Code can easily be identified and contains encoded data, which means resulting AR applications could read the code to get a URL pointing to a remote model to be downloaded (and then superimposed on the video feed). This approach has been discussed and tested in [77].

Circular markers have also been explored and [29] in fact describes a long-range solution using target-like markers, whose components are shown in figure 3.11.

![Circular markers proposed by Christen et al.](https://artoolkit.org/documentation/lib/exe/detail.php?id=3_Marker_Training%3Amarker_about&media=diagram.jpg)

#### 3.2.2 Natural features

Image feature detectors and descriptors can be used in a wide range of applications, such as image classification or object recognition, but are an essential
part of many AR applications. They also are vital for solving the simultaneous localization and mapping problem that will be discussed in section 3.3.

Depending on the specific task, different feature detectors and descriptors can be appropriate, this section will discuss some of the most popular methods.

Feature detectors

Feature detectors aim to find interesting key points in an image. Those local features should be invariant to position, rotation and scale changes. They should also be robust to occlusion, noise, illumination change and sufficiently distinct from each other.

Feature detectors are generally classified into 3 categories: single-scale detectors, multi-scale detectors and affine-invariant detectors [60].

Single-scale detectors

The first group, single-scale detectors, can deal with positional and rotational changes of the image. They can also handle noise and illumination changes but they are not designed to cope with scaling issues. They can therefore be helpful for "standard" AR applications that simply need a marker but cannot be used when the same scene has to be recognized from different viewpoints that cause scaling changes.

A typical example is Harris detector [59] that detects corners and edges by looking at image gradients (that measure changes in the image’s intensity or color). The general intuition behind it is pictured in figure 3.12.

From the source image, a value that depends on the gradient is assigned to each pixel (results are displayed in the second picture of figure 3.13, where high values are shown in red). Using a threshold, only interesting points are kept (the white dots from the third picture of the same figure). Finally, only local maxima are kept (the highest values from the "local neighborhood"), those are the key points returned as output, as shown on another example in figure 3.14.

Figure 3.12: Interesting points in an image: effect of translating a windows [152]

https://inst.eecs.berkeley.edu/~cs194-26/fa14/upload/files/proj7B/cs194-fj/kristen_curry_proj7.2/HearstMining/red5.jpg
3.2. Vision-based tracking

Other methods and adapted versions of the same general idea have been proposed, such as SUSAN [154] that detects corners with lower-level processing (using a circular mask centered on each pixel of the image to then compare that center pixel’s intensity to the rest of the circular area). FAST (Features from Accelerated Segment Test) [133, 134] is a well-known corner detector, that also looks for features by using a circle around a candidate point. This time though, the point $p$ is considered a valid feature if a set of contiguous pixels on the circle are brighter than the candidate (see figure 3.15). To enhance performance, some invalid points can be quickly filtered by only checking a few of those points, e.g. 1, 5, 9 and 13 on the same figure.
Chapter 3. Motion tracking and related computer vision techniques

Multi-scale detectors
Harris detector can easily be adapted to deal with scale changes if the exact deformation is known. Unfortunately, in real world scenarios, scale change is unknown and we need to find ways to detect interesting points at varying scales.

By identifying regions of the image that have properties (e.g. brightness or color) that are different from their surroundings, we form blobs. To find them, a first way is to use Laplacian of Gaussian (LoG) filters that start by smoothing the image with a Gaussian filter (essentially blurring it) then use a Laplacian filter (very noise sensitive, hence the prior smoothing operation) to get those blobs. LoG can therefore be applied for finding a location-specific scale for a region of an image, which means it is possible to automatically select the right scale for that region. Lindeberg proposed a multi-scale approach that does exactly that [95].

As LoG is computationally expensive, Lowe proposed a more efficient solution that is based on a difference of gaussians (DoG) at different scales [97]. The input image is successively smoother by a Gaussian filter and resampled. LoG is then essentially approximated by subtracting two successive smoothed images.

Affine-invariant detectors

Single-scale detectors discussed previously exhibit invariance to translations and rotations. For their part, multi-scale detectors can also handle uniform scaling and, to some extent, affine invariance (ability to handle shear mapping and non-uniform scaling in addition to previous operations; with shear essentially referring to the possibility of viewing the scene from a different perspective while preserving parallelism, as seen on figure 3.16).

![Figure 3.16: Shear mapping and its preservation of parallelism (and therefore perpendicularity)](https://qph.ec.quoracdn.net/main-qimg-c00a7e8ac5efc42e412270723ec3d459)

Affine-invariant detectors go one step further: they are able to handle significant affine transformations. Several existing feature detectors have been extended to handle those perspective issues and methods have been developed, such as the one by Mikolajczyk and Schmid [102], proposed in 2004.
The idea of that method is to extract the characteristic shape (as opposed to the characteristic scale discussed before) of the detected feature. The circles are in fact replaced by ellipses with axis lengths that depend on the same gradient-dependent value used in Harris detector [59] we discussed before.

![Figure 3.17: Mikolajczyk and Schmid’s proposal key concept: characteristic shape, with ellipses of different sizes](image)

### Feature descriptors

Now that feature detectors have been introduced, meaning key points can be detected, it is time to "describe" them so that they can be recognized (and matched). For that purpose, feature descriptors (sometimes referred to as feature extractors), are used. They work by analyzing the feature’s surroundings (the pixels around it) and often use techniques described in the previous section.

In 2004, Lowe presented SIFT (Scale-Invariant Feature Transform) [98], a detector and descriptor that uses 4 major steps:

- Scale-space extrema detection: use DoG to detect interesting points
- Keypoint localization: Determine location and scale, then select keypoints based on their stability
- Orientation assignment: Using gradient directions, assign orientations to the keypoints (this step ensures the method is invariant to orientation, scale and location)
- Keypoint descriptor: Measure gradients in the region around each keypoint, transform them so that they are more robust to distortion and illumination changes, then store them

In 2006, Bay, Tuytelaars, and Van Gool presented SURF (Speeded Up Robust Features) [9], designed as a more efficient version of SIFT.

SIFT and SURF are both patented and use gradients (relatively computationally-expensive and heavy on storage) as descriptors. For these reasons, binary image descriptors have been developed with low power mobile devices in mind. They essentially replace gradient-based encoding by a compact binary string. A few examples of algorithms using them are given below.
BRIEF (Binary Robust Independent Elementary Features) \[24\] was introduced in 2010 by Calonder et al. and is the first technique that uses binary descriptors. The idea is that, within the local region of a feature, pixels are compared by pairs (chosen using different methods). Depending on how their intensity relates, a binary value is assigned and by concatenating those bits, we get the binary string used as descriptor.

Other well-known examples of binary image descriptors (therefore based on Calonder et al.’s work) include BRISK (Binary Robust Invariant Scalable Keypoints) \[91\], ORB (Oriented FAST and Rotated BRIEF) \[137\] and FREAK (Fast Retina Keypoints) \[2\].

A lot of comparisons between the aforementioned algorithms and their combination (i.e. one of them used for feature detection, another for feature description) have been published. Some are meant to compare these algorithms based on their application to 3D object matching \[108\], pedestrian detection \[141\] or visual tracking \[56\] (particularly useful for AR and SLAM, that will be discussed in section 3.3). Other focus their analysis on binary descriptors \[62\] or specific evaluation criteria, such as repeatability rate (how stable the features are under different transformations) and information content (how features differ) \[143\].

### Feature matching

Once features have been found and described, the next task is to match them in different images. Various possibilities are being used for that purpose, relying on nearest-neighbor approaches or randomized kd-tree forests like the "fast library for approximate nearest neighbors" (FLANN) \[109\]. However, those methods are not suitable for binary descriptors, which are typically compared using the Hamming distance (essentially counting the number of mismatching bits between the binary strings \(a\) and \(b\), that show as 1’s after computing \(a \oplus b\) (XOR operation)).

### 3.3 SLAM

The simultaneous localization and mapping (SLAM) problem describes the mapping of an unknown environment by a mobile robot. Without any previous knowledge of its surroundings, the robot therefore has two problems to solve at once: localize itself and map the environment.

SLAM is heavily tied with AR, especially spatial-aware AR, as devices need to get a sense of their environment to successfully integrate the augmented content in their surroundings. This section therefore introduces the basics of the problem.

Even though several researchers were already working on mapping and localization at the time, the structure of the SLAM problem and the coining of the acronym was first presented in \[40\] by Durrant-Whyte, Rye, and Nebot in 1996.

In \[39\], Durrant-Whyte and Bailey give a formal definition of that problem as pictured in figure 3.18 and described below. A mobile robot freely
moves in an environment while using its sensor to observe unknown landmarks that are assumed to be stationary.

At time $k$, we have:

\[
\begin{align*}
    x_k & \text{ the vector describing the position/orientation of the robot} \\
    u_k & \text{ the vector, applied at time } k - 1 \text{ to move the vehicle to } x_k \text{ at time } k \\
    m_i & \text{ the vector describing the position of the } i\text{th stationary landmark} \\
    z_{ik} & \text{ the observation, taken from the robot, of the } i\text{th landmark at time } k
\end{align*}
\]

\[\text{Figure 3.18: The SLAM problem, as described in [39]}\]

Motion tracking and natural feature extraction techniques described in previous sections are the usual base tools for solving the SLAM problem, as the landmarks mentioned in the formal definition typically are natural features extracted with algorithms such as those discussed in section 3.2.2. The position of the camera and the observed landmarks are then inferred but, as noise and inaccuracies are unavoidable, methods have to be developed to cope with them. A very widely-used option is the extended Kalman [76] filter (EKF), sometimes with specially trained neural networks [61, 68].

Researchers have been very active trying to solve the problem in the last decades and many approaches have in fact been explored. Some involve multiple robots building the map together while others focus on solving the same problem for hand-held or hand-worn devices (such as PTAM [80]).
Recent years have seen compelling commercial products start to appear, with Google Tango\(^\text{17}\) or Microsoft Hololens (further discussed in 6.1) both providing spatial mapping capabilities.

\[^{17}\text{https://get.google.com/tango/}\]
Chapter 4

Virtual Reality and its use cases

VR can be used in a very wide range of domains. It is in fact impossible to name all of those fields of applications but a number of examples of use cases and ongoing researches will be discussed in this chapter. Even though entertainment currently is the main driver for VR, we will focus on more "serious" applications.

4.1 Healthcare

VR users can experience a sense of presence [145] and that is key to various treatments for mental conditions (e.g., anxiety and specific phobias). In fact, a term has even been coined: virtual reality exposure therapy (VRET). That kind of treatment has been applied to flying phobia [15], fear of heights [136, 84], or spiders [25, 54], but also to post-traumatic stress disorder (PTSD), with applications to World Trade Center victims [34] or individuals suffering from combat-related PTSD [130] like US Vietnam [135] or Iraq [57] veterans.

But VR applications to medicine are not limited to psychiatric and behavioral healthcare, it has also been used in neuropsychology, for the assessment and rehabilitation of disabilities that result from brain injury, memory impairments or attention deficits [132], while others have focused on stroke rehabilitation [70, 88, 139]. VR can also be used for pain distraction (e.g. during painful interventions) and even chronic pain [117, 151].

4.2 Computer-aided design

Computer-aided design (CAD) describes the use of computers to create, analyze and optimize designs. It can be applied to many domains, including mechanical, electronic or even orthopedic design activities as well as the architecture, engineering and construction (AEC) industry. In the context of architectural design, the term "Computer-aided architectural design" (CAAD) is often used to describe softwares that accommodate the specific needs of the field. Those systems can often benefit from computer-generated environments, the term "Virtual engineering" has even been coined and is now widely used in the automotive industry [73]. Even though they are not always combined with VR, those systems can really benefit from that technology as a strong sense of presence has also been assessed in that context [63].
Chapter 4. Virtual Reality and its use cases

For example, in the aerospace industry or more specifically in cockpit design, VR can greatly help in evaluating the ergonomics of complex interfaces. A pilot can visualize how the product would look and perform usual actions on it, as pictured in figure 4.1. The way he interacts with it can be analyzed and engineers can then validate their virtual prototype.

Figure 4.1: Usual actions performed by a pilot in the "after landing" procedure [128]

The technology has also been used for assembly [71, 149] and manufacturing [110] simulations, as well as scientific visualization (as part of a product’s design phase). The latter category includes fluid simulations such as the airflow visualization tool [21, 22] developed by NASA.

But VR is not limited to single-user experiences and it is in fact a great tool for participatory design [20, 23, 119] where all stakeholders are involved.

4.3 Education and training

The ability to visualize 3D models and environments as if you were part of it can prove very useful in an educational and training contexts, especially when coupled with haptic feedback. Learning by doing is not really different from what one can do through a first-person virtual experience, which means similar learning benefits should be observed.

For instance, surgical education typically involves animal cadavers or plastic mock-ups but using VR training in that context [8] was proven to be successful [150] with significant improvements on the trainees’ part. Similarly, interesting results were achieved by using the technology for teaching in various domains such as anatomy [112], foreign languages or supply chain. The "fun" aspect of VR probably also helps in keeping users’ attention high, which positively affects their performance.

Being able to simulate extreme conditions that would be costly or even risky for users is also a big advantage of virtual reality training, with examples dedicated to firefighters and fire victims [163] or even astronauts [42, 6].
While VR experiences cannot really be a substitute for real travel, the ability to be transported into places that no longer exist, even if it is only virtual, is attractive.

In fact, VR was already being used for cultural heritage [52, 118] prior to the democratization of HMDs for the general public.

More recent examples include applications that allows virtual visitors to see ancient Rome[1] or Jerusalem[2] (a capture from within the application is shown in figure 4.2).

![Ancient Jerusalem experienced in VR](https://img.purch.com/h/1400/aHR0cDovL3d3dy5saXZlc2NpZW5jZS5jb20vaW1hZ2VzL2kvMDAwLzA4OS8yMzQvb3JpZ2luYWwvamVydXNhbGVtLXZyLWIuanBn)

**Figure 4.2: Ancient Jerusalem experienced in VR**

[1] http://colosseumlives.com/
[2] https://play.google.com/store/apps/details?id=com.ARE.AncientJerusalemVR
[3] https://img.purch.com/h/1400/aHR0cDovL3d3dy5saXZlc2NpZW5jZS5jb20vaW1hZ2VzL2kvMDAwLzA4OS8yMzQvb3JpZ2luYWwvamVydXNhbGVtLXZyLWIuanBn
Chapter 5

Exploring Augmented Reality applications

As with VR, AR can be used in very different applications. This chapter will discuss a few domains where AR proved helpful. Some examples will voluntarily look similar to what was presented in the previous chapter because, in fact, there is an overlap between AR and VR’s fields of application.

5.1 Entertainment

The entertainment industry provides a major field of application for AR. It is once again impossible not to mention the game Pokémon Go as it truly brought AR to the masses (at a very basic level but it did help popularize the concept). Another common use of AR is in sports broadcasting, as already mentioned in section 2.1.

Nevertheless, AR entertainment is not limited to smartphones and TVs. Skemmi\(^1\) a Belgian company, fully understands that as they are specialized in mass-interactive experiences generally involving AR. A significant part of their work involves cinema events, where everyone in the public can play an AR game broadcasted on the giant screen, using gestural interaction (e.g. by slicing virtual fruits with an arm movement).

For the launch of Disney’s Vaiana, they even enhanced the experience by turning the usual intra-cinema competition to a cinema battle. Two different rooms were in fact competing against each other, trying to paddle as fast as possible so that a pirogue could reach its goal.\(^2\)

But that kind of experience is not only intended at entertaining people, as psychology studies\(^3\) have shown that collective experiences have a positive impact on several aspects and can be used to strengthen collective identity or self-esteem for example in the context of teambuilding activities.

Other somewhat popular applications of AR in the entertainment industry are card\(^4\) and board\(^5\) games. Commercial examples of the former include Genesis\(^6\) and Drakerz\(^7\) pictured in figure 5.1.

\(^1\)http://www.skemmi.com/
\(^2\)https://vimeo.com/194798563
\(^3\)http://www.genesisaugmented.com/
\(^4\)https://www.drakerz.com/
\(^5\)https://i.ytimg.com/vi/yEaR116swnQ/maxresdefault.jpg
Augmenting those "physical" games with animated characters and other elements can enable very interesting and immersive experiences, by combining the tangible aspect of traditional games with the aesthetics and animations of computer games.

5.2 Retail industry, with a practical example

As part of an entrepreneurial project and together with 4 other students, we developed an AR catalog application. The idea is that potential purchases such as furnitures can sometimes look good but, once bought, they do not always fit in their final environment (wrong dimensions, colors or "style").

In order to avoid that problem, we propose CatARlog, a mobile application that uses AR to let end customers visualize how objects will look in their own interior (proof-of-concept shown in figure 5.2). Users simply have to download the store-specific application and place a flyer on the floor that is used as an AR marker. Then, the application lets them choose from a set of models from that store.

Similar applications have been developed, for large companies such as IKEA, Lego or Converse. With CatARlog, we are also targeting SMBs (small and medium size businesses) that generally do not have the same kind of budget.

Figure 5.3 shows that most people are interested in that kind of application (the data comes from a survey we conducted with 50 "random" persons). Additionally, a study from Retail Perceptions that questioned more than a thousand US citizens about AR shows, among other things, that 71% of shoppers would shop at a retailer more often if they offered such a service. That interest shown by end users is encouraging for the future of AR in retail and a few companies do believe in its potential in that context, such as Augment and DigitalBridge.

6 http://www.retailperceptions.com/2016/10/the-impact-of-augmented-reality-on-retail/  
7 www.augment.com/  
8 http://digitalbridge.eu/
5.3 Healthcare

As with VR, the sense of presence (here enhanced by the fact that the user can actually see his own hands and the real world) can help in exposure therapies for several types of psychological problems, such as spider and cockroach phobias [14, 75]. Figure 5.4 pictures different steps of an AR exposure therapy. More recent work that also includes environmental awareness and does not require markers can be seen at [114].

Other applications include an AR treatment for phantom limb pain [26], overlays for surgeries [47, 140] and post-stroke hand rehabilitation [65].
5.4 Education and training

In education, AR has been used to teach anatomy [13], maths and geometry [78], engineering [92] or even astronomy [44]. Figure 5.5a shows one of these examples in a collaborative teaching context, with a superimposed model of a cone being worked on.

AR has also been employed to train individuals for assembly tasks [161, 126], including motherboard installation as shown in figure 5.5b, and military operations, such as room-clearing scenarios [18] and in the context of urban terrains [96].

5.5 Architecture, engineering and construction

As with VR, applications in the AEC industry are numerous, with information overlaid onto buildings using a mobile application [7] or students’ creations superimposed in the middle of a square (see figure 5.6) to evaluate their design [124].

When maintaining roads or constructing buildings and if the corresponding data/application are available, AR can help visualize underground pipes and subsurface data, as discussed in [89, 131, 142]. Companies like Bentley have also shown interest in using that kind of subsurface visualization.

https://communities.bentley.com/other/old_site_member_blogs/bentley_employees/b/stephanecotes_blog/archive/2012/06/18/augmented-reality-for-subsurface-utilities-further-improving-perception
5.6 Culture and tourism

Binoculars are widely used in specific touristic locations, allowing visitors to see and zoom in the surroundings for a few minutes by putting a coin in. Those experiences can be augmented [45] by integrating elements on top of the view: some information or pointers and even buildings or structures. As most people (or at least families) now own a smartphone, similar experiences can be offered via mobile devices [81, 165].

Similarly, cultural heritage sites can benefit from the technology, by superimposing monuments that have since disappeared or virtual inhabitants of the corresponding period [113, 159]. Another use of AR in that context has been described in [28], where hard-to-observe animal engravings are highlighted in real time on a smartphone. Similarly, SAR can be used to colorize archaeological artifacts [129], as seen in figure 5.7. Those artifacts can also be felt if an haptic interface is being coupled with AR, as in [36], where the technology was used in museums to create the illusion of feeling objects that are otherwise impossible to touch.
5.7 Industrial maintenance and complex tasks

For the highly demanding technical work that is often required in industrial maintenance, AR can come to help, for instance by providing additional information superimposed on an object or by displaying a 3D model of the piece being maintained \[146\]. It has been used for helping welders in the automotive industry \[41\] as well as the personnel responsible for maintaining a pump \[55\].

As operators sometimes need the help of a remote engineer, collaborative AR systems can be a better way of indicating specific pieces than describing them orally. Such remote assistance AR systems were developed in \[16\] and \[10\].

Complex assembly tasks typically require the use of manuals containing instructions. Those manuals can be (partly) replaced by AR systems displaying the same instructions and adding world-anchored indications. Those kinds of applications have been developed for domains such as the aerospace \[148\] or food \[123\] industries. Figure 5.8 shows usual augmented elements used in the latter context.
Chapter 6

Spatial-aware augmented reality

This chapter will present what we chose to call spatial-aware augmented reality (spatial-mapped AR or surroundings-aware AR would have been valid names too). This subset of AR has a better understanding of the environment than traditional AR, it does not simply add augmented content "blindly", neither does it rely on (fiducial) markers to place that content.

6.1 Microsoft Hololens

An example of a device enabling spatial-aware experiences is Microsoft Hololens. The real innovation with this headset is that it combines several advanced technologies into a single, autonomous and portable device (shown in figure 6.1).

![Figure 6.1: Microsoft Hololens, a spatial-aware AR HMD](https://compass-ssl.surface.com/assets/f5/2a/f52a1f76-0640-4a37-a650-51b0902f8427.jpg)

6.1.1 The hardware

The Hololens uses see-through lenses and 2 light engines to project the augmented content. It automatically calibrates pupillary distance, has a "holographic resolution" of 2.3M total light points and a "holographic density" of more than 2.5k light points per radian. In order to scan the environment, it uses 4 dedicated cameras, in addition to the depth camera and the 2MP photo/video camera (see figure 6.2). It also has an IMU (inertial measurement unit, to track head movements), 4 microphones, an ambient light sensor and a spatial sound system. More information can be found at [27][30]. As discussed in section 3.1.4, an IMU alone is not sufficient to track something continuously. Unfortunately, Microsoft did not reveal the method they used to remove unavoidable drifts but they did explain [1] that spatial mapping
was using natural feature extraction (see section 3.2.2) so it is very likely that positional tracking is corrected that way.

![Microsoft Hololens cameras and sensors](https://az835927.vo.msecnd.net/sites/mixed-reality/Resources/images/Sensor_bar.jpg)

**Figure 6.2:** Microsoft Hololens cameras and sensors

To process sensors data and camera feeds, Microsoft created a custom chip called the Holographic Processing Unit (HPU). More information on that particular component of the device can be found in [17].

### 6.1.2 "Mixed reality" experiences

Microsoft and lots of websites describe the Hololens as a mixed reality device. While this is not fundamentally false, it leads to confusion as MR is thus often misunderstood as "AR with real world understanding and anchoring". As explained in chapter 2, MR is a superset of AR, therefore neither a subset nor something different from AR. In fact, the Hololens is an AR device and Hololens applications are AR experiences.

That being said, spatial-aware AR has many current and potential applications. Just like VR, entertainment and more specifically video games have embraced the technology. But there are also lots of industrial applications, most of whom are yet to be explored.

For example, the AEC (architecture, engineering and construction) industry could benefit from such a technology. They already transitioned from 2D hand drawings to 2D digital plans, then to 3D models. But current 3D models are currently stuck behind a 2D screen. What if they could be integrated into the real world (say on a table) and designers could collaborate on it in real time (potentially even remotely)? Figure 6.3 shows Sketchup for Hololens, an example of a commercial AEC application from Trimble [3].

The technology can also be used in maintenance (or more generally when expertise is needed) where lengthy manuals can be replaced by an application that directly integrates instructions and indicators onto the corresponding parts of the object that is being worked on. Combined with things like voice recognition, it is also possible to achieve a quick and hands-free experience that improves productivity.

[17] https://az835927.vo.msecnd.net/sites/mixed-reality/Resources/images/Sensor_bar.jpg
[3] https://img.reality.news/img/74/25/63614387056309/0/trimble-releases-sketchup-viewer-first-commercial-hololens-application-windows-store-1280x600.jpg
An example of such an application (that also includes remote collaboration) for "pipe maintenance" can be seen in [11]. Lots of other scenarios in the retail industry or in education benefiting from the Hololens and similar devices can be imagined but will not be discussed here.

6.2 Other devices

In this section, we will talk about competitors to the Hololens, with a few devices able to deliver similar experiences (or believed to be).

6.2.1 Direct competitors

Meta

Meta is an American company that developed Meta 1 and, since December 2016, Meta 2. They both are see-through AR HMDs equipped with a 3D camera, capable of recognizing gestures and superimposing holograms into the real world. While Meta 1 was somewhat limited (e.g. with a 23-degree field of view), Meta 2 is aiming at competing with the Hololens. Its main characteristics are:

- 90-degree field of view (much better than the Hololens’ speculated 30 degrees)
- 2560×1440 display resolution
- 720p front-facing camera
- hand tracking capabilities
- tethered (requires a Windows 8+ PC)
- can be preorderred for $949

[3] https://www.metavision.com/
[4] http://doc-ok.org/?p=1223
Chapter 6. Spatial-aware augmented reality

Magic Leap

Magic Leap is a very secretive American startup that was able to raise $1.4 billion from investors including major companies such as Google, Qualcomm or Alibaba Group. Since then, the company has been working in "stealth mode" and whether their product achieves what can be seen in their concept video is currently unknown (so are the hardware specifications and the price). We only know they want to create a standalone device with a very wide field of view.

DAQRI

DAQRI is another American company selling AR headsets. It should also be mentioned that in 2015 they acquired ARToolWorks, the company that initially released ARToolKit. They first started with an AR helmet (to meet the safety requirements in specific industries) with special components such as thermal sensors but are now also selling "standard" AR glasses for $4995. Both of those devices are using a RealSense 3D camera (from Intel, based on technologies from the Belgian company SoftKinetic) and are offering a 44-degree field of view.

Others

Other devices worth mentioning are castAR and ODG’s R-8 and R-9. Those see-through glasses are yet to be released but promise very high field of view.

6.2.2 Other versions of the Hololens

A "Hololens v2" was meant to be released (an improved and consumer-ready version) but the project has been sidelined. Instead, the focus will be on a "Hololens v3" planned for 2019, that will most likely introduce major improvements. In addition to that, Microsoft revealed they partnered with several companies (Acer, Asus, Dell, HP and Lenovo) to create tethered VR headsets with cameras. As of now, it hasn’t been clarified whether those cameras will enable video see-through AR or "simply" provide real world information. Those headsets should be available for sale later this year (2017) for $300.

6.3 A practical example: HoloEscape

As an illustration of what spatial-aware AR can achieve and in order to validate the practical usability of such applications, a game has been developed as part of the present master’s thesis. HoloEscape runs on the Hololens, involves spatial mapping and basic understanding as well as gestural interaction and gaze input.

https://www.youtube.com/watch?v=kPMHcanq0xM
6.3. A practical example: HoloEscape

It has been presented during the "Printemps des Sciences" on March 25-26, 2017 (a public event in Mons, Belgium). As end-user (informal) feedback was intended to be gathered during that event and given that the public mainly consisted of families with children, developing a game seemed like an obvious choice and was in fact confirmed by the constant line of people wanting to try it.

The device (Microsoft Hololens) was chosen because it is so innovative: being able to see the real world through autonomous glasses capable of superimposing holograms anchored in the environment (occluding the models if necessary thanks to the spatial mapping capabilities) had never been achieved before. In addition to that, as the device was fairly new (it was not even purchasable in Belgium when this master’s thesis started), the ability to develop software for it was a unique chance that could not be missed.

6.3.1 Game description

The game itself is a "reversed tower defense" where the player controls a virtual ball using gaze input. His goal is to make it reach the end of a holographic road (displayed on the floor) without touching electric walls. Hostile turrets can be added by positioning printed images (which means spectators can effectively take part in the game). Once in position, those turrets will constantly shoot at the player that needs to dodge the resulting laser beams.

When the ball touches a wall or is hit by a laser beam, the player looses one life (out of 3). To enhance spectators’ experience, a few mobile mini-games were developed and allowed players to affect the Hololens gameplay. For instance, getting bad scores on a Flappy Bird clone led to a bigger ball (harder to control) and faster beams whereas winning on a Breakout clone could lead to an "unbreakable" ball and slower beams.

Figure 6.4 helps clarifying the concept (a video is also available at [32]).

![HoloEscape: Game concept](image)

6.3.2 Technologies

The main technologies the project is built on will be introduced in this section. Potential alternatives will be discussed and choices will be explained. That includes the game engine as well as features such as spatial mapping.
and gaze input. Finally, the tool used to recognize printed images will be presented and evaluated.

**Unity**

Unity[^7] is a leading game engine, used by millions of people every day (according to their website). It can produce games for many desktop, mobile and console platforms and is recommended by Microsoft for building 3D Hololens applications. Other alternatives include UrhoSharp[^8] (.NET bindings of Urho3D[^9]) and even direct DirectX projects.

Because it is recommended and widely used, Unity has been chosen. It should however be mentioned that the process for building Hololens applications is a bit unusual. Whereas "standard" platforms can be targeted via a simple compilation in Unity’s editor, building for Hololens requires an additional step as Unity is only able to create an intermediary Visual Studio[^10] solution. That solution can then be compiled to the actual application (inside Visual Studio). The need to rely on two different compilers leads to issues that will be further discussed in section [6.3.3](#).

**Spatial Mapping**

Using the hardware described in section [6.1.1](#) the Hololens is able to reconstruct triangle meshes representing its understanding of the environment (example shown in figure [6.5](#)).

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[^7]: http://unity3d.com/
[^8]: https://developer.xamarin.com/guides/cross-platform/urho/introduction/
[^9]: https://urho3d.github.io/
[^10]: https://www.visualstudio.com/

figure-space-sound-used-help-visually-impaired-navigate-with-hololens.1280x600.jpg
In the "Holographic Academy"[12] (containing a few tutorials explaining how to use the device with Unity) and in the "HoloToolkit for Unity"[13] (a GitHub repository gathering lots of scripts and components related to Hololens development), Microsoft shows how to access and process that spatial mapping data.

The components they provide come with a few parameters to address the needs of the developers (mesh "resolution", "scanning zone", delay between spatial mapping updates, etc).

In the context of HoloEscape, the only thing we need to extract from that mesh is the floor (to place holographic roads and the ball). To achieve that goal, a possibility is to use HoloToolkit’s `SurfaceMeshesToPlanes`[14] that will "convert" the meshes to planes. In our case, we are only interested in horizontal planes as they are good candidates for the floor. It has been chosen to then select the lowest of those candidates that is close enough to the user. In most cases, this will correctly pick the plane that corresponds to the floor of the room the user is in. The only issue I encountered is when the user looks at a contiguous room through a glass during the scanning process. If that other room is lower than the room the user is in, the wrong plane will be picked. As those conditions are quite far-fetched and easily avoidable by not looking at that other room, no specific logic was implemented to prevent the issue from happening.

Another possibility would have been to use Spatial Understanding scripts[15]. Those components go beyond a simple "meshes to planes" conversion, they provide a better and higher-level understanding of the environment (example shown on figure 6.6).

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[12] https://developer.microsoft.com/en-us/windows/mixed-reality/academy
[13] https://github.com/Microsoft/HoloToolkit-Unity
[14] https://github.com/Microsoft/HoloToolkit-Unity/blob/master/Assets/HoloToolkit/SpatialMapping/Scripts/SpatialProcessing/SurfaceMeshesToPlanes.cs
[15] https://github.com/Microsoft/HoloToolkit-Unity/tree/master/Assets/HoloToolkit/SpatialUnderstanding

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**Figure 6.6**: Spatial understanding capabilities[15]
These scripts were initially developed by Asobo Studios\textsuperscript{17} a video game development company based in Bordeaux, France. They had to develop those features for their games\textsuperscript{18} but then decided to share the corresponding code. Their work is available through a DLL (compiled from their codebase in C++) exposed to Unity in the HoloToolkit.

One should note that it is also possible (using the device portal available through a local website) to obtain a complete mesh for an entire "mixed reality capture", as seen in figure\textsuperscript{6.7}

![Figure 6.7: A mesh obtained from a mixed reality capture that corresponds to several rooms\textsuperscript{19}](https://az835927.vo.msecnd.net/sites/mixed-reality/Resources/images/SU_ShapeQuery.jpg)

**Gaze input**

As explained in section\textsuperscript{6.3.1} gaze input is used to control the virtual ball in our game. We already know that the IMU (see section\textsuperscript{6.1.1}) is tracking head movements but we have yet to explain how that data can be used by developers. That part is in fact very simple: the main camera of the Unity scene is "mapped" to head movements, its forward vector therefore indicates where the user is looking. It is then fast forward to search for an intersection between a target surface and the semi-straight line produced by that vector (see figure\textsuperscript{6.8}).

As with any kind of sensor, there is noise in the raw data received from the IMU which can cause jitter when displaying the cursor. Once again, the HoloToolkit proves to be useful as it contains a \texttt{GazeStabilizer} script that can be used to smooth that data (different smoothing filters can of course be applied if needed).

\textsuperscript{16} https://az835927.vo.msecnd.net/sites/mixed-reality/Resources/images/SU_ShapeQuery.jpg
\textsuperscript{17} http://www.asobostudio.com/
\textsuperscript{18} http://www.asobostudio.com/games#filter=.hololens
\textsuperscript{19} http://www.sharpgis.net/image.axd?picture=image_131.png
\textsuperscript{20} https://abhijitjana.files.wordpress.com/2016/05/image31.png
6.3. A practical example: HoloEscape

Image recognition and tracking

In order to add turrets, one has to place printed images on the floor and "show" them to the camera. A very well-known, open-source and widely used possibility is ARToolkit\(^{21}\). Unfortunately, it does not currently support Hololens even though Qian et al. announced they successfully integrated ARToolkit 5 with it [120].

Vuforia\(^{22}\) officially supports Hololens and has therefore been chosen. It is capable of recognizing and tracking 3D objects (to some extent) but also image targets (using natural feature extraction, see section 3.2.2). The process’ principle is shown in figure 6.9 (many AR solutions are based on the same principle). The quality of the tracking in fact highly depends on the features (sharp, spiked, chiseled details in the image) that Vuforia was able to extract from the original image. Advices on how to choose and improve those target images can be found in [93]. The chosen image that contains the university’s logo is not perfect but is still rated with 5 stars out of 5 by Vuforia’s target manager, because as seen in the central picture of figure 6.9, enough features were found in the background image (mostly on persons) and around the letters.

![Image tracking principle](https://vuforia.com/)

With the aim of validating the image recognition solution, a test was undertaken (by the author) and is explained below. The user places a printed image on the floor, then moves a few meters back. With the Hololens (running an application developed for that purpose) on his head, the user slowly walks towards the image. In the process, he makes sure to keep it in sight (a cursor is displayed, much like the yellow circle on figure 6.8, and always stays on the printed picture). The situation is pictured on figure 6.10.

\(^21\)https://artoolkit.org/
\(^22\)https://vuforia.com/
When the user comes close enough to the image, the camera recognizes it. The distance between the device and the paper is measured (the length of $\vec{d}$ on the figure).

That procedure was tested with a photograph that is classified as an excellent tracking candidate by Vuforia’s target manager (5 stars out of 5, indicating that many features have been detected and are spread across the image). The picture was printed in 5 different sizes (labeled with their approximate ISO paper format equivalent) to observe the effect of changing the target’s size on the "recognition distance". The corresponding results are displayed in Table 6.1 and Figure 6.11. Note that A7 is so small it requires the user to bend a little.

| Label | Image dimensions (cm) | Avg. distance (m) | Std. deviation (m) |
|-------|-----------------------|-------------------|--------------------|
| A3    | 38.4 x 26.9           | 2.1320294         | 0.029664227        |
| A4    | 28.5 x 20             | 2.0558848         | 0.016190217        |
| A5    | 20 x 14               | 1.8263826         | 0.029573648        |
| A6    | 14.6 x 10.2           | 1.5392008         | 0.003787432        |
| A7    | 10.5 x 7.3            | 1.135628          | 0.017326755        |

Table 6.1: Effect of a varying image size on Vuforia (for Hololens) "recognition distance" - results

As shown by those results and as expected, increasing the size of the image helps making it easier to recognize, but that recognizability doesn’t increase linearly. Another surprising fact is that the standard deviation is relatively low (less than 2% for all sizes) which means the results were particularly stable.

### 6.3.3 Issues and validation

Rather than using a virtual ball, the initial goal was to integrate Sphero, a robotic ball controlled via Bluetooth, into the game. The technical difficulties that prevented that from happening will be discussed here.

[23]http://www.sphero.com/
Connecting Hololens to Sphero directly

Several factors are causing issues when trying to make Hololens and Sphero communicate:

- Hololens runs on Windows 10, thus able to run "Windows 10 applications" (technically UWP for Universal Windows Platform). Older APIs are therefore not available on the device.

- The Sphero SDK for Unity only works on Android and iOS which means the Windows SDK has to be used. That SDK hasn’t been updated in years (last commit was made in 2013 and it does not work on recent versions of Windows 10 that are required for the Hololens).

- Unity uses a modified version of Mono\(^\text{24}\) that roughly corresponds to .NET 3.5 (10 years old). Newer APIs are therefore not available in Unity (and some obsolete APIs used in Unity’s Mono cannot be used on the Hololens).

Even though the Hololens is capable of Bluetooth connectivity, those issues mean that connecting the device with Sphero is not as simple as it should be. Several forks of the official Sphero SDK for Windows do exist, some of them are relatively up-to-date and, in a blog post \([156]\), Taulty even managed to make it work on the Hololens (using SoftPlay’s reworked version\(^\text{25}\) of the Sphero SDK).

Unfortunately, that experiment as well as the aforementioned forks are not targeting 3D Unity applications but "only" standard UWP. What Taulty did is not replicable and building the corresponding library (RobotKit.dll from SoftPlay’s GitHub) did not work as exceptions were thrown when trying to retrieve the Bluetooth RFCOMM service that correspond to the Sphero. At the time of writing, no solution to that problem has been found, neither by myself nor by Taulty.

\(^{24}\)\url{http://www.mono-project.com/}
\(^{25}\)\url{https://github.com/SoftPlay/SpheroWindows/}
Using a relay

As a direct connection did not seem possible, another approach was tried: an Android application acting as a relay. In fact, the Sphero SDK for Android works fine so the ball could be controlled by an Android application that communicates with the Hololens using WebSockets (corresponding diagram shown in figure 6.12). The exchanged messages use FlatBuffers\textsuperscript{26} to format the data in binary buffers (different message types are declared, such as STATUS_REQUEST or DIRECTIVE, and corresponding data structures are defined) to be as efficient as possible.

\textbf{Figure 6.12:} Android application as a relay using WebSockets

However, using WebSockets appeared to be a bit slow for real-time control and tracking of the ball (trusting Sphero’s own tracking), as shown by the tests that were carried out. The corresponding procedure is explained below.

As we are interested in bidirectional communication and because it would be very difficult to synchronize the Hololens with the Android application, we measured the round-trip time (RTT) i.e. the total time needed for a message sent from the Hololens to return to it.

To be more precise, the Hololens application starts counting when it sends a message to the phone. As the Android application receives that message, it replies with a predefined response instantly. When the Hololens receives that reply, it stops the counter and stores the result. It then waits for a second and the process can start again (117 complete "trips"). In order to limit interferences, the Wi-Fi used for that communication is created on a laptop, with no other devices connected to it. As only one person at a time can wear the Hololens, the setup has also been tested with live streaming enabled. The corresponding results are given in table 6.2 and figure 6.13. Note that the testing procedure does not take the bluetooth transmission (from the phone to the ball) into account, but it is considered negligible.

As there was a significant amount of outliers, two metrics were added: the median RTT and the number of RTT above 0.4s (that are not shown on the plot for readability). Those results show that without streaming, the solution could be viable but would need some extra precautions to handle "silent periods" as some messages took way too long. A potential solution could be to run a timer on the Android application that tells the ball to stop moving

\textsuperscript{26}https://google.github.io/flatbuffers/
6.3. A practical example: HoloEscape

|                  | Without streaming | With streaming |
|------------------|-------------------|----------------|
| Number of "trips"| 117               | 117            |
| Minimum RTT (s)  | 0.0165062         | 0.03204155     |
| Maximum RTT (s)  | 2.780609          | 4.49617        |
| Average RTT (s)  | 0.125426211       | 0.306582943    |
| Standard deviation (s) | 0.322630263 | 0.558482321 |
| Median RTT (s)   | 0.03330231        | 0.134491       |
| Number of RTTs > 0.4s | 5             | 19             |

Table 6.2: Round-trip times using WebSockets, with and without streaming - results

When no directive has been received for a certain delay. On the other hand, we can see the effect of having streaming enabled: the number of RTTs above 0.4s increases (to reach a bit more than 16% of all samples) and that is hardly acceptable, even though the median value is reasonable.

Tracking the ball

Despite those mixed results, coupling a somewhat slow WebSockets relay with an effective tracking system could still yield interesting results. Unfortunately, there is currently no way of accessing the raw depth data the Hololens processes, which means that tracking dynamic objects is difficult and less accurate than it could be with that data. Consequently, the only option to track the ball is the front RGB camera (red-green-blue, a standard color camera). Vuforia is capable of tracking some 3D objects but Sphero is a rolling sphere, almost entirely white (that can only be lit by a solid color)
so it is not suitable in itself as there is no interest point to track. To overcome that issue, a cube with bearing balls has been 3D printed (see figure 6.14).

The idea was to put it around the Sphero ball (made with a translucent material so that the ball’s color is reflected) with "trackable" images on some of its sides. That solution would provide a relatively unstable tracking (issues when the user would move his head and stop gazing at the ball/cube) and, as the size of the tracked images would be comparable to the "A7" image from table 6.1, similar tracking distances would be observed (the user would have to stay close to the ball). More importantly, it would not allow streaming as only one process can have access to the Hololens’ front (and only accessible) camera at any time. As this project was to be presented in public events, such a limitation was inappropriate and the virtual ball was the only viable solution.

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27 https://developer.microsoft.com/en-us/windows/mixed-reality/mixed_reality_capture_for_developers#simultaneous_mrc_limitations
Chapter 7

Current limitations and foreseeable prospects

VR enables a wide range of applications and can deeply change a set of human endeavors, as seen in chapter 4 through short-term experiences. The necessary equipment is relatively mature, whereas AR’s potential (in particular through head-worn displays) currently is more restrained by the underlying technological needs. However, once these problems will be solved, AR could be integrated in our daily lives. This chapter will discuss current limitations and future prospects, for both fields.

7.1 Displays

In their famous and previously cited paper [104], Milgram et al. identified the needs for optical see-through displays: “accurate and precise, low latency body and head tracking, accurate and precise calibration and viewpoint matching, adequate field of view, [...] a snug (no-slip) but comfortable and preferably untethered head-mount”.

While the Hololens’ head tracking and viewpoint matching are already compelling, inside an untethered (autonomous and wireless) device, the field of view still is a major issue. As previously discussed (section 6.2.1), competitors announced much wider field of views but whether their promises will be delivered remains to be seen.

As already mentioned in section 2.1, retinal displays could very well be the future as they could potentially combine more portability, a very wide field of view and less eye-tiredness. The VR industry could benefit from it but it would truly be a game changer for AR as small field of views and unsuitability for outdoor use are the usual issues for see-through devices. Reducing eye-tiredness is also key to long term (maybe even permanent) use.

Many people wear glasses constantly so size and weight should not really be an issue but if tinier displays are desired, contact lenses are also a possibility. In fact, in 2014, Samsung patented [79] such AR lenses in South Korea. The patent application describes the lenses as equipped with a camera, an antenna and several sensors (according to a brief translation from [51]).

The patent shows that it might be a work in progress but lenses are so small that compelling experiences look out of reach in the near future. Even though simple overlays could potentially be superimposed at some point,
with the computing part handled by a smartphone, latency would probably be a problem. Another issue to solve is power supply, how would lenses get enough energy to run the hardware?

### 7.2 Computing resources and sensors

As the hardware gets shorter, more powerful and more efficient, head-mounted devices will continue to evolve, with more capabilities in "more wearable" devices.

In terms of pure computing power, it is highly likely that we will see more ASICs (application-specific integrated circuits) inside those devices, that will be better suited for particular purposes such as computer vision (e.g. DSP for digital signal processor and VPU for vision processing unit).

Conventional silicon chips have already been pushed to their limits in terms of speed (or will soon be). In fact, recent years have focused on parallelizing several processors to try and compensate for the lack of speed increase. That being said, graphene processors are the future and will be much faster and smaller while requiring much less power \[^{[147]}\]. Those properties could obviously be helpful for wearable devices.

Similarly, computer vision and the SLAM problem will keep being active research domains. As algorithms get better, be it in terms of accuracy, robustness or complexity, spatial-aware AR experiences will improve.

All those elements will probably lead to more broadly-available and affordable head-worn devices capable of enabling compelling AR/VR experiences but the upcoming addition of depth cameras to mobile phones will most likely play an even more important role in the democratization of spatial-aware AR. In fact, devices equipped with such depth sensors start to appear, e.g. with the ZenFone AR\[^{[\text{1}]}\], a high-end smartphone oriented towards consumers and that should be released in summer 2017.

### 7.3 Interaction

Wearing an HMD enabling immersive or world anchored 3D experiences also requires special considerations with regards to how users can interact with it.

Firstly, new kinds of UIs (user interfaces) need to be designed. In standard computer 3D applications such as games, information is often overlaid onto the virtual camera’s view (e.g. to display a health bar). The same concept cannot be applied to optical see-through devices such as the Hololens, as the rendering’s proximity to the user’s eyes would be uncomfortable. The usual solution is to use a 3D UI integrated into the environment (possibly positioned depending on the user’s gaze direction) instead of being attached to the camera. An example of such a UI is shown in figure [7.1] \[^{[\text{1}]}\]

\[^{[\text{1}]}\] \(\text{https://www.asus.com/Phone/ZenFone-AR-ZS571KL/}\)
In order to interact with those UIs and other models, it is also necessary to provide some kind of gestural interaction as traditional input devices such as mouses and keyboards are generally not desirable (they are not adapted for that purpose). Speech recognition could also be an important part of those new interfaces but it still is a difficult problem, especially in noisy environments.

On a more personal note, I do believe that the usual approach of trying to "map" traditional input to a new kind of input (e.g. replacing a mouse click with a click gesture) might be the best approach for short term goals but is not advisable for the long run. New kinds of interactive environments should go along with new paradigms, even though technology is not ready yet for the futuristic AR interfaces (picture shown in figure 7.2) seen in the previously mentioned Iron Man movie.

**Figure 7.2**: Iron man’s futuristic AR interface

https://www.windowscentral.com/sites/wpcentral.com/files/styles/larger/public/field/image/2015/07/motorcycle-hololens.jpg?itok=gqeREJqm

https://www.youtube.com/watch?v=mRldmFgRfc
Another way to get user input is by using brain-computer interfaces (BCIs). The idea is to analyze neural activity and map it to some kind of basic action. Different types of techniques can be used to monitor neural activity, invasive (implanted directly into the grey matter) and non-invasive (external devices) methods exist, with measurements typically taken by EEGs (electroencephalograms, analyzing the brain’s activity) or EMGs (electromyogram, analyzing muscular activity). Figure 7.3 pictures a non-intrusive system used in the context of neurorehabilitation in stroke.

Interesting results have been achieved, with promising applications, especially for individuals with muscular handicaps [53, 64, 85] but also for certain types of autism, with BCI sometimes coupled with VR [153].

However, current state-of-the-art methods are limited to a set of predefined simple actions and requires a significant amount of preliminary user training, mainly in research settings. Understanding complex intent (e.g. "go back to main menu") is completely out of reach as of now.

So far, this section only talked about what the user sees and how to get input from him but another important contribution will most likely come from haptic feedback. While VR enables immersive experiences, it is generally limited to viewing and listening to virtual content, which means only 2 out of 5 traditional senses can be used by the computer to send information to the user. In those experiences, the users sometimes manipulate virtual objects but they usually cannot physically touch them. Haptic interfaces can be used to make users feel those virtual objects, by applying appropriate forces where needed.

A popular haptic interface is PHANTOM [100], developed by Massie, Salisbury, et al. in 1994. Since then, the impact of such a technology has then been analyzed [58], so was its complementarity with VR [13]. Commercial products also start to appear with (among many others) haptic gloves from

[FIGURE 7.3: A EEG-based BCI example with robotic feedback]
ManusVR\(^5\) and even lots of complete body suits being in development such as the Teslasuit\(^6\) or Hardlight’s suit\(^7\).

### 7.4 Social acceptance

Judging by the criticism around Google Glass\(^8\) when it was released, mainly related to privacy issues, it looks like the general public is not ready to accept other people wearing cameras most of the time. While the HMDs discussed in chapter\(^6\) dodged the issue by focusing on industrial applications, the problem remains for ordinary individuals.

On top of that, AR/VR wearables usually look futuristic but cannot really be considered good-looking by most people. While this is not crucial for their ability to deliver functional experiences, it might be important for the general public to embrace them.

Those concerns need to be addressed if we ever want to see AR wearables integrated into our daily lives, and the miniaturization of those devices will certainly help with that.

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5. <https://manus-vr.com/>
6. <https://teslasuit.io/>
7. <http://www.hardlightvr.com/>
8. <https://www.google.com/glass/start/>
Chapter 8

Conclusion

I certainly learned a lot by completing this master’s thesis, in terms of technologies and potential applications for AR and VR, two fields I am very interested in. I truly believe both AR and VR will be very beneficial to various industries in a relatively short term but exploring the possibilities also raised my expectations for our future daily lives.

Receiving the chance to work with a device as innovative as the Hololens was really attractive and the trouble related to the issues encountered while developing the game are no match to the joy of presenting it and seeing smiles on the players’ face. I cannot thank the Microsoft Innovation Center enough for that opportunity.

I wish (and in fact plan on) extending the game’s capabilities as real world geometry and objects could potentially be used to decide where the level’s roads should be placed, using some kind of spatial-aware procedural level generation.

As said before, AR and VR will keep growing and it is definitely exciting, provided that the necessary evolutions in human-computer interactions follow the same path. Work remains to be done on several aspects of those domains and I do hope researchers will achieve significant progress to allow ubiquitous computing (every time, everywhere) and a seamless blending between reality and virtuality. Maybe even by developing wearable devices capable of switching back and forth between AR and VR modes with adaptive transparency?
Bibliography

[1] Microsoft HoloLens’s YouTube account. Microsoft HoloLens: The Science Within - Keeping Holograms in Place. URL: https://www.youtube.com/watch?v=TneGSeqVAXQ

[2] Alexandre Alahi, Raphael Ortiz, and Pierre Vandergheynst. “Freak: Fast retina keypoint”. In: Computer vision and pattern recognition (CVPR), 2012 IEEE conference on. Ieee. 2012, pp. 510–517.

[3] Aviad Almagor. Mixed Reality for The AEC Industry Extending Trimble’s Product Capabilities with Microsoft HoloLens. Tech. rep. 2016. URL: http://buildings.trimble.com/sites/buildings.trimble.com/files/white_papers/Trimble_White_Paper_Mixed_Reality_for_The_AEC_Industry.pdf

[4] Troels L Andersen et al. “Designing an augmented reality board game with children: the battleboard 3D experience”. In: Proceedings of the 2004 conference on Interaction design and children: building a community. ACM. 2004, pp. 137–138.

[5] Kai Keng Ang et al. “Clinical study of neurorehabilitation in stroke using EEG-based motor imagery brain-computer interface with robotic feedback”. In: Engineering in Medicine and Biology Society (EMBC), 2010 Annual International Conference of the IEEE. IEEE. 2010, pp. 5549–5552.

[6] Hirofumi Aoki, Charles M Oman, and Alan Natapoff. “Virtual-reality-based 3D navigation training for emergency egress from spacecraft”. In: Aviation, space, and environmental medicine 78.8 (2007), pp. 774–783.

[7] Hyojoon Bae, Mani Golparvar-Fard, and Jules White. “High-precision vision-based mobile augmented reality system for context-aware architectural, engineering, construction and facility management (AEC/FM) applications”. In: Visualization in Engineering 1.1 (2013), p. 3.

[8] Cagatay Basdogan et al. “VR-based simulators for training in minimally invasive surgery”. In: IEEE Computer Graphics and Applications 27.2 (2007).

[9] Herbert Bay, Tinne Tuytelaars, and Luc Van Gool. “Surf: Speeded up robust features”. In: Computer vision–ECCV 2006 (2006), pp. 404–417.

[10] Samir Benbelkacem et al. Augmented reality platform for collaborative E-maintenance systems. INTECH Open Access Publisher, 2011.

[11] Stephane Côté from Bentley Systems. Hololens Plant Maintenance. URL: https://www.youtube.com/watch?v=QTuKcm8s4QQ
[12] Oliver Bimber and Ramesh Raskar. “Modern Approaches to Augmented Reality”. In: *ACM SIGGRAPH 2006 Courses*. SIGGRAPH ’06. Boston, Massachusetts: ACM, 2006. ISBN: 1-59593-364-6. DOI: 10.1145/1185657.1185796.

[13] Tobias Blum et al. “mirracle: An augmented reality magic mirror system for anatomy education”. In: *Virtual Reality Short Papers and Posters (VRW), 2012 IEEE*. IEEE. 2012, pp. 115–116.

[14] CM Botella et al. “Mixing realities? An application of augmented reality for the treatment of cockroach phobia”. In: *Cyberpsychology & Behavior* 8.2 (2005), pp. 162–171.

[15] C Botella et al. “Treatment of flying phobia using virtual reality: Data from a 1-year follow-up using a multiple baseline design”. In: *Clinical Psychology & Psychotherapy* 11.5 (2004), pp. 311–323.

[16] Sébastien Bottecchia, Jean-Marc Cieutat, and Jean-Pierre Jessel. “TAC: augmented reality system for collaborative tele-assistance in the field of maintenance through internet”. In: *Proceedings of the 1st Augmented Human International Conference*. ACM. 2010, p. 14.

[17] Peter Bright. *Microsoft sheds some light on its mysterious holographic processing unit*. URL: https://arstechnica.com/information-technology/2016/08/microsoft-sheds-some-light-on-its-mysterious-holographic-processing-unit/.

[18] Dennis G Brown, Joseph T Coyne, and Roy Stripling. “Augmented reality for urban skills training”. In: *Virtual Reality Conference, 2006*. IEEE. 2006, pp. 249–252.

[19] Gerd Bruder et al. “Augmented Virtual Studio for Architectural Exploration”. In: *Proceedings of the Virtual Reality International Conference (VRIC)*. IEEE Press, 2010, pp. 1–8. URL: http://viscg.uni-muenster.de/publications/2010/BSVH10a.

[20] Fabio Bruno and Maurizio Muzzupappa. “Product interface design: A participatory approach based on virtual reality”. In: *International journal of human-computer studies* 68.5 (2010), pp. 254–269.

[21] Steve Bryson and Michael Gerald-Yamasaki. “The distributed virtual windtunnel”. In: *Proceedings of the 1992 ACM/IEEE conference on Supercomputing*. IEEE Computer Society Press. 1992, pp. 275–284.

[22] Steve Bryson and Creon Levit. “The virtual wind tunnel”. In: *IEEE Computer graphics and Applications* 12.4 (1992), pp. 25–34.

[23] Hans-Jörg Bullinger et al. “Towards user centred design (UCD) in architecture based on immersive virtual environments”. In: *Computers in Industry* 61.4 (2010), pp. 372–379.

[24] Michael Calonder et al. “Brief: Binary robust independent elementary features”. In: *Computer Vision–ECCV 2010* (2010), pp. 778–792.
[25] Albert S. Carlin, Hunter G. Hoffman, and Suzanne Weghorst. “Virtual reality and tactile augmentation in the treatment of spider phobia: a case report”. In: Behaviour Research and Therapy 35.2 (1997), pp. 153–158. ISSN: 0005-7967. DOI: https://doi.org/10.1016/S0005-7967(96)00085-X.

[26] Francesco Carrino et al. “Augmented reality treatment for phantom limb pain”. In: International Conference on Virtual, Augmented and Mixed Reality. Springer. 2014, pp. 248–257.

[27] Windows Dev Center. HoloLens hardware details. URL: https://developer.microsoft.com/en-us/windows/mixed-reality/hololens_hardware_details

[28] Omar Choudary et al. “MARCH: mobile augmented reality for cultural heritage”. In: Proceedings of the 17th ACM international conference on Multimedia. ACM. 2009, pp. 1023–1024.

[29] Oliver Christen et al. “Target Marker: A Visual Marker for Long Distances and Detection in Realtime on Mobile Devices”. In: 2nd International Conference of Machine Vision and Machine Learning. 2013.

[30] Seth Colaner. What’s Inside Microsoft’s HoloLens And How It Works. URL: http://www.tomshardware.com/news/microsoft-hololens-components-hpu-28nm,32546.html

[31] C. Conn et al. “Virtual Environments and Interactivity: Windows to the Future”. In: ACM SIGGRAPH 89 Panel Proceedings. SIGGRAPH ’89. Boston, Massachusetts, USA, 1989, pp. 7–18. ISBN: 0-89791-353-1. DOI: 10.1145/77276.77278.

[32] Adrien Coppens. Introducing HoloEscape. URL: https://www.youtube.com/watch?v=mBOXsopgGzo

[33] Carolina Cruz-Neira et al. “The CAVE: Audio Visual Experience Automatic Virtual Environment”. In: Commun. ACM 35.6 (June 1992), pp. 64–72. ISSN: 0001-0782. DOI: 10.1145/129888.129892.

[34] Joann Difede and Hunter G Hoffman. “Virtual reality exposure therapy for World Trade Center post-traumatic stress disorder: A case report”. In: Cyberpsychology & Behavior 5.6 (2002), pp. 529–535.

[35] Digi-Capital. After mixed year, mobile AR to drive $108 billion VR/AR market by 2021. Jan. 2017. URL: http://www.digi-capital.com/news/2017/01/after-mixed-year-mobile-ar-to-drive-108-billion-vrar-market-by-2021/

[36] Mariza Dima, Linda Hurcombe, and Mark Wright. “Touching the past: haptic augmented reality for museum artefacts”. In: International Conference on Virtual, Augmented and Mixed Reality. Springer. 2014, pp. 3–14.

[37] Ulf Dressler. Japanese High-Tech Helps People With Low Vision See Again. 2015. URL: https://www.japanindustrynews.com/2015/11/japanese-high-tech-helps-people-with-low-vision-see-again/
[38] Emmanuel Dubois, Laurence Nigay, and Jocelyne Troccaz. “Combinaisons le monde virtuel et le monde réel–classification et principes de conception”. In: Actes des Rencontres Jeunes Chercheurs en Interaction Homme-Machine (2000), pp. 31–34.

[39] Hugh Durrant-Whyte and Tim Bailey. “Simultaneous localization and mapping: part I”. In: IEEE robotics & automation magazine 13.2 (2006), pp. 99–110.

[40] Hugh Durrant-Whyte, David Rye, and Eduardo Nebot. “Localization of autonomous guided vehicles”. In: Robotics Research. Springer, 1996, pp. 613–625.

[41] Florian Echtler et al. “The intelligent welding gun: Augmented reality for experimental vehicle construction”. In: Virtual and augmented reality applications in manufacturing. Springer, 2004, pp. 333–360.

[42] Timothy Everson et al. “Astronaut Training using Virtual Reality in a Neutrally Buoyant Environment”. In: KnE Engineering 2.2 (2017), pp. 319–327.

[43] Te-Yung Fang et al. “Evaluation of a haptics-based virtual reality temporal bone simulator for anatomy and surgery training”. In: Computer methods and programs in biomedicine 113.2 (2014), pp. 674–681.

[44] Stéphanie Fleck and Gilles Simon. “An augmented reality environment for astronomy learning in elementary grades: An exploratory study”. In: Proceedings of the 25th Conference on l’Interaction Homme-Machine. ACM. 2013, p. 14.

[45] F Fritz, A Susperregui, and Maria Teresa Linaza. “Enhancing cultural tourism experiences with augmented reality technologies”. In: 6th International Symposium on Virtual Reality, Archaeology and Cultural Heritage (VAST). 2005.

[46] Henry Fuchs and Jeremy Ackerman. “Displays for Augmented Reality: Historical Remarks and Future Prospects”. In: Mixed Reality. ISMR ’99. Boston, Massachusetts, 1999. DOI: 10.1007/978-3-642-87512-0_2

[47] Henry Fuchs et al. “Augmented reality visualization for laparoscopic surgery”. In: International Conference on Medical Image Computing and Computer-Assisted Intervention. Springer. 1998, pp. 934–943.

[48] Philippe Fuchs, Guillaume Moreau, and Alain Berthoz. “Le traité de la réalité virtuelle(Vol. 1, Fondements et interfaces comportementales)”. In: Sciences mathématiques et informatique (2003).

[49] Thomas A. Furness. The application of head-mounted displays to airborne reconnaissance and weapon delivery. Wright-Patterson Air Force Base, Ohio, USA, 1969.

[50] Thomas A. Furness. “The Super Cockpit and its Human Factors Challenges”. In: Proceedings of the Human Factors Society Annual Meeting 30.1 (1986), pp. 48–52. DOI: 10.1177/154193128603000112.
[51] Michel G. Samsung is working on smart contact lenses, patent filing reveals. URL: https://www.sammobile.com/2016/04/05/samsung-is-working-on-smart-contact-lenses-patent-filing-reveals/.

[52] Athanasios Gaitatzes, Dimitrios Christopoulos, and Maria Roussou. “Reviving the past: cultural heritage meets virtual reality”. In: Proceedings of the 2001 conference on Virtual reality, archeology, and cultural heritage. ACM. 2001, pp. 103–110.

[53] Xiaorong Gao et al. “A BCI-based environmental controller for the motion-disabled”. In: IEEE Transactions on Neural Systems and Rehabilitation Engineering 11.2 (2003), pp. 137–140.

[54] A Garcia-Palacios et al. “Virtual reality in the treatment of spider phobia: a controlled study”. In: Behaviour Research and Therapy 40.9 (2002), pp. 983–993. ISSN: 0005-7967. DOI: https://doi.org/10.1016/S0005-7967(01)00068-7.

[55] Luis Eduardo Garza et al. “Augmented Reality Application for the Maintenance of a Flapper Valve of a Fuller-kynion Type M Pump”. In: Procedia Computer Science 25 (2013), pp. 154–160. ISSN: 1877-0509. DOI: http://dx.doi.org/10.1016/j.procs.2013.11.019.

[56] Steffen Gauglitz, Tobias Höllerer, and Matthew Turk. “Evaluation of interest point detectors and feature descriptors for visual tracking”. In: International journal of computer vision 94.3 (2011), pp. 335–360.

[57] Maryrose Gerardi et al. “Virtual reality exposure therapy using a virtual Iraq: case report”. In: Journal of traumatic stress 21.2 (2008), pp. 209–213.

[58] Google. Glass. URL: https://developers.google.com/glass/.

[59] Chris Harris and Mike Stephens. “A combined corner and edge detector.” In: Alvey vision conference. Vol. 15. 50. Citeseer. 1988, pp. 10–5244.

[60] M Hassaballah, Aly Amin Abdelmgeid, and Hammam A Alshazly. “Image Features Detection, Description and Matching”. In: Image Feature Detectors and Descriptors. Springer, 2016, pp. 11–45.

[61] Simon S Haykin et al. Kalman filtering and neural networks. Wiley Online Library, 2001.

[62] Jared Heinly, Enrique Dunn, and Jan-Michael Frahm. “Comparative evaluation of binary features”. In: Computer Vision–ECCV 2012. Springer, 2012, pp. 759–773.

[63] Arsalan Heydarian et al. “Immersive virtual environments versus physical built environments: A benchmarking study for building design and user-built environment explorations”. In: Automation in Construction 54 (2015), pp. 116–126.

[64] Ulrich Hoffmann et al. “An efficient P300-based brain–computer interface for disabled subjects”. In: Journal of Neuroscience methods 167.1 (2008), pp. 115–125.
[65] Hossein Mousavi Hondori et al. “A spatial augmented reality rehab system for post-stroke hand rehabilitation.” In: MMVR. 2013, pp. 279–285.

[66] Olivier Hugues, Philippe Fuchs, and Olivier Nannipieri. “New augmented reality taxonomy: Technologies and features of augmented environment”. In: Handboook of augmented reality. Springer, 2011, pp. 47–63.

[67] Duy-Nguyen Ta Huynh et al. “Art of defense: a collaborative handheld augmented reality board game”. In: Proceedings of the 2009 ACM SIGGRAPH symposium on video games. ACM. 2009, pp. 135–142.

[68] Youji Iiguni, Hideaki Sakai, and Hidekatsu Tokumaru. “A real-time learning algorithm for a multilayered neural network based on the extended Kalman filter”. In: IEEE Transactions on Signal processing 40.4 (1992), pp. 959–966.

[69] The Numediart Institute and Drag On Slide. Giant Play : projection publique. URL: https://www.youtube.com/watch?v=qE8acHX9ABs

[70] David Jack et al. “Virtual reality-enhanced stroke rehabilitation”. In: IEEE transactions on neural systems and rehabilitation engineering 9.3 (2001), pp. 308–318.

[71] Sankar Jayaram, Hugh I Connacher, and Kevin W Lyons. “Virtual assembly using virtual reality techniques”. In: Computer-aided design 29.8 (1997), pp. 575–584.

[72] Nivart Jean François, Radhwan Ben Madhkour, and Romuald Deshayes. “Monumental projections”. In: QPSR of the numediart research program (2010).

[73] Mr Mangqin Jiang. “Virtual reality boosting automotive development”. In: Virtual Reality & Augmented Reality in Industry. Springer, 2011, pp. 171–180.

[74] Fujitsu Journal. Expand Your World by “Seeing the Unseeable” Retinal Imaging Laser Eyewear: the Smart Eyewear that Projects Images onto the Retina (Part I). URL: http://journal.jp.fujitsu.com/en/2016/12/13/01/

[75] M Carmen Juan et al. “Using augmented reality to treat phobias”. In: IEEE computer graphics and applications 25.6 (2005), pp. 31–37.

[76] Rudolph Emil Kalman. “A New Approach to Linear Filtering and Prediction Problems”. In: Transactions of the ASME–Journal of Basic Engineering 82.Series D (1960), pp. 35–45.

[77] Tai-Wei Kan, Chin-Hung Teng, and Mike Y Chen. “QR code based augmented reality applications”. In: Handbook of augmented reality. Springer, 2011, pp. 339–354.

[78] Hannes Kaufmann and Dieter Schmalstieg. “Mathematics and geometry education with collaborative augmented reality”. In: Computers & Graphics 27.3 (2003), pp. 339–345.
[79] Tae Ho Kim et al. Smart contact lenses for augmented reality and methods of manufacturing and operating the same. Korean Patent No. 1020140129517. 2014.

[80] Georg Klein and David Murray. “Parallel tracking and mapping for small AR workspaces”. In: Mixed and Augmented Reality, 2007. ISMAR 2007. 6th IEEE and ACM International Symposium on. IEEE. 2007, pp. 225–234.

[81] Chris D Kounavis, Anna E Kasimati, and Efpraxia D Zamani. “Enhancing the tourism experience through mobile augmented reality: Challenges and prospects”. In: International Journal of Engineering Business Management 4 (2012), p. 10.

[82] Oliver Kreylos. Lighthouse tracking examined. URL: http://doc-ok.org/?p=1478.

[83] Oliver Kreylos. Pure IMU-based Positional Tracking is a No-go. URL: https://www.youtube.com/watch?v=_q_8d0E3tDk.

[84] Merel Krijn et al. “Treatment of acrophobia in virtual reality: The role of immersion and presence”. In: Behaviour research and therapy 42.2 (2004), pp. 229–239.

[85] Andrea Kübler et al. “Patients with ALS can use sensorimotor rhythms to operate a brain-computer interface”. In: Neurology 64.10 (2005), pp. 1775–1777.

[86] Albert HT Lam et al. “ART: augmented reality table for interactive trading card game”. In: Proceedings of the 2006 ACM international conference on Virtual reality continuum and its applications. ACM. 2006, pp. 357–360.

[87] J. Lanier. A Vintage Virtual Reality Interview. Ed. by Whole Earth Review. 1988. URL: http://www.jaronlanier.com/vrint.html.

[88] Kate Laver et al. “Virtual reality for stroke rehabilitation”. In: Stroke 43.2 (2012), e20–e21.

[89] Shaun W Lawson and John RG Pretlove. “Augmented reality for underground pipe inspection and maintenance”. In: Photonics East (ISAM, VVDC, IEMB). International Society for Optics and Photonics. 1998, pp. 98–104.

[90] Wonwoo Lee, Woontack Woo, and Jongweon Lee. “Tarboard: Tangible augmented reality system for table-top game environment”. In: 2nd International Workshop on Pervasive Gaming Applications, PerGames. Vol. 5. 2.1. 2005.

[91] Stefan Leutenegger, Margarita Chli, and Roland Y Siegwart. “BRISK: Binary robust invariant scalable keypoints”. In: Computer Vision (ICCV), 2011 IEEE International Conference on. IEEE. 2011, pp. 2548–2555.

[92] Fotis Liarokapis et al. “Web3D and augmented reality to support engineering education”. In: World Transactions on Engineering and Technology Education 3.1 (2004), pp. 11–14.
[93] Vuforia’s Developer Library. *Natural Features and Image Ratings*. URL: https://library.vuforia.com/articles/Solution/Natural-Features-and-Ratings.

[94] Junguo Lin et al. “Retinal projection head-mounted display”. In: *Frontiers of Optoelectronics* 10.1, 1 (2017), p. 1. DOI: 10.1007/s12200-016-0662-8.

[95] Tony Lindeberg. “Feature detection with automatic scale selection”. In: *International journal of computer vision* 30.2 (1998), pp. 79–116.

[96] Mark A Livingston et al. *An augmented reality system for military operations in urban terrain*. Tech. rep. DTIC Document, 2002.

[97] David G Lowe. “Distinctive image features from scale-invariant keypoints”. In: *International journal of computer vision* 60.2 (2004), pp. 91–110.

[98] David G Lowe. “Distinctive image features from scale-invariant keypoints”. In: *International journal of computer vision* 60.2 (2004), pp. 91–110.

[99] Wendy E Mackay. “Augmenting reality: A new paradigm for interacting with computers”. In: *La recherche* 3 (1996).

[100] Thomas H Massie, J Kenneth Salisbury, et al. “The phantom haptic interface: A device for probing virtual objects”. In: *Proceedings of the ASME winter annual meeting, symposium on haptic interfaces for virtual environment and teleoperator systems*. Vol. 55. 1. Citeseer. 1994, pp. 295–300.

[101] Peter Meer. *Lecture notes from Robust Computer Vision*, Department of Electrical and Computer Engineering, Rutgers University. 2017.

[102] Krystian Mikolajczyk and Cordelia Schmid. “Scale & affine invariant interest point detectors”. In: *International journal of computer vision* 60.1 (2004), pp. 63–86.

[103] Paul Milgram and Fumio Kishino. “A taxonomy of mixed reality visual displays”. In: *IEICE TRANSACTIONS on Information and Systems* 77.12 (1994), pp. 1321–1329.

[104] Augmented reality: a class of displays on the reality-virtuality continuum. Vol. 2351. 1995, pp. 282–292. DOI: 10.1117/12.197321.

[105] Paul Milgram et al. *Augmented reality: a class of displays on the reality-virtuality continuum*. 1995. DOI: 10.1117/12.197321.

[106] Eray Molla and Vincent Lepetit. “Augmented reality for board games”. In: *Mixed and Augmented Reality (ISMAR), 2010 9th IEEE International Symposium on*. IEEE. 2010, pp. 253–254.

[107] Dirty Monitor for Mons 2015. *MAPPING 360° Carré des Arts*. URL: https://www.youtube.com/watch?v=zm5Gc-nISow.

[108] Pierre Moreels and Pietro Perona. “Evaluation of features detectors and descriptors based on 3d objects”. In: *International journal of computer vision* 73.3 (2007), pp. 263–284.
[109] Marius Muja and David G Lowe. “Scalable nearest neighbor algorithms for high dimensional data”. In: IEEE Transactions on Pattern Analysis and Machine Intelligence 36.11 (2014), pp. 2227–2240.

[110] Tariq S Mujber, Tamas Szecsi, and Mohammed SJ Hashmi. “Virtual reality applications in manufacturing process simulation”. In: Journal of materials processing technology 155 (2004), pp. 1834–1838.

[111] Niantic. Pokémon Go. URL: http://www.pokemongo.com

[112] Daren T Nicholson et al. “Can virtual reality improve anatomy education? A randomised controlled study of a computer-generated three-dimensional anatomical ear model”. In: Medical education 40.11 (2006), pp. 1081–1087.

[113] Zakiah Noh, Mohd Shahrizal Sunar, and Zhigeng Pan. “A review on augmented reality for virtual heritage system”. In: International Conference on Technologies for E-Learning and Digital Entertainment. Springer. 2009, pp. 50–61.

[114] HIT Lab NZ. Interactive Augmented Reality Exposure Treatment. URL: https://www.youtube.com/watch?v=7FLyDEdQ_vk

[115] Charles B Owen, Fan Xiao, and Paul Middlin. “What is the best fiducial?” In: Augmented Reality Toolkit, The First IEEE International Workshop. IEEE. 2002, 8–pp.

[116] Dario Páez et al. “Psychosocial effects of perceived emotional synchrony in collective gatherings.” In: Journal of Personality and Social Psychology 108.5 (2015), p. 711.

[117] Thomas D Parsons and Zina Trost. “Virtual reality graded exposure therapy as treatment for pain-related fear and disability in chronic pain”. In: Virtual, Augmented Reality and Serious Games for Healthcare 1. Springer, 2014, pp. 523–546.

[118] Daniel Pletinckx et al. “Virtual-reality heritage presentation at Ename”. In: IEEE MultiMedia 7.2 (2000), pp. 45–48.

[119] Alenka Poplin. “Playful public participation in urban planning: A case study for online serious games”. In: Computers, Environment and Urban Systems 36.3 (2012), pp. 195–206.

[120] Long Qian et al. Comprehensive Tracker Based Display Calibration for Holographic Optical See-Through Head-Mounted Display. 2017. arXiv:1703.05834.

[121] Ewa Radziszewska. Investing in the Matrix? Augmented and Virtual Reality Show High Investment Potential. URL: https://www.credit-suisse.com/be/en/articles/articles/news-and-expertise/2016/10/en/investing-in-matrix.html

[122] Ramesh Raskar et al. “The Office of the Future: A Unified Approach to Image-based Modeling and Spatially Immersive Displays”. In: Proceedings of the 25th Annual Conference on Computer Graphics and Interactive Techniques. SIGGRAPH ’98. New York, NY, USA, 1998, pp. 179–188. ISBN: 0-89791-999-8. DOI: 10.1145/280814.280861
[123] Guido Maria Re and Monica Bordegoni. “An augmented reality framework for supporting and monitoring operators during maintenance tasks”. In: International Conference on Virtual, Augmented and Mixed Reality. Springer. 2014, pp. 443–454.

[124] Ernest Redondo et al. “Augmented and Geo-Located Information in an Architectural Education Framework”. In: International Conference on Virtual, Augmented and Mixed Reality. Springer. 2014, pp. 15–26.

[125] H. Regenbrecht et al. “Using Augmented Virtuality for Remote Collaboration”. In: Presence: Teleoper. Virtual Environ. 13.3 (July 2004), pp. 338–354. ISSN: 1054-7460. DOI: 10.1162/1054746041422334

[126] Dirk Reiners et al. “Augmented reality for construction tasks: Doorlock assembly”. In: Proc. IEEE and ACM IWAR 98.1 (1998), pp. 31–46.

[127] Philippe Renevier. “Mobile Collaborative Mixed Systems : Design and Development”. PhD thesis. Université Joseph-Fourier - Grenoble I, June 2004.

[128] Loukas Rentzos et al. “Using VR for Complex Product Design”. In: International Conference on Virtual, Augmented and Mixed Reality. Springer. 2014, pp. 455–464.

[129] Brett Ridel. “Interaction techniques, personalized experience and surface reconstruction for spatial augmented reality”. PhD thesis. Université de Bordeaux, Oct. 2016.

[130] Albert Rizzo et al. “Virtual reality exposure therapy for combat-related PTSD”. In: Post-traumatic stress disorder. Springer, 2009, pp. 375–399.

[131] Gethin W Roberts et al. “The use of augmented reality, GPS and INS for subsurface data visualization”. In: FIG XXII International Congress. 2002, pp. 1–12.

[132] F David Rose, Barbara M Brooks, and Albert A Rizzo. “Virtual reality in brain damage rehabilitation: review”. In: Cyberpsychology & behavior 8.3 (2005), pp. 241–262.

[133] Edward Rosten and Tom Drummond. “Fusing points and lines for high performance tracking”. In: Computer Vision, 2005. ICCV 2005. Tenth IEEE International Conference on. Vol. 2. IEEE. 2005, pp. 1508–1515.

[134] Edward Rosten and Tom Drummond. “Machine learning for high-speed corner detection”. In: Computer vision–ECCV 2006 (2006), pp. 430–443.

[135] Barbara Olasov Rothbaum et al. “Virtual reality exposure therapy for PTSD Vietnam veterans: A case study”. In: Journal of traumatic stress 12.2 (1999), pp. 263–271.

[136] Barbara Olasov Rothbaum et al. “Virtual reality graded exposure in the treatment of acrophobia: A case report”. In: Behavior Therapy 26.3 (1995), pp. 547–554.
[137] Ethan Rublee et al. “ORB: An efficient alternative to SIFT or SURF”. In: Computer Vision (ICCV), 2011 IEEE International Conference on. IEEE. 2011, pp. 2564–2571.

[138] Eva-Lotta Sallnäs, Kirsten Rassmus-Gröh, and Calle Sjöström. “Supporting presence in collaborative environments by haptic force feedback”. In: ACM Transactions on Computer-Human Interaction (TOCHI) 7.4 (2000), pp. 461–476.

[139] Gustavo Saposnik, Mindy Levin, Stroke Outcome Research Canada (SORCan) Working Group, et al. “Virtual reality in stroke rehabilitation”. In: Stroke 42.5 (2011), pp. 1380–1386.

[140] Yoshinobu Sato et al. “Image guidance of breast cancer surgery using 3-D ultrasound images and augmented reality visualization”. In: IEEE Transactions on Medical Imaging 17.5 (1998), pp. 681–693.

[141] Cameron Schaeffer. “A Comparison of Keypoint Descriptors in the Context of Pedestrian Detection: FREAK vs. SURF vs. BRISK”. In: Cité en (2013), p. 12.

[142] Gerhard Schall et al. “Handheld augmented reality for underground infrastructure visualization”. In: Personal and ubiquitous computing 13.4 (2009), pp. 281–291.

[143] Cordelia Schmid, Roger Mohr, and Christian Bauckhage. “Evaluation of interest point detectors”. In: International Journal of computer vision 37.2 (2000), pp. 151–172.

[144] Brian T. Schowengerdt et al. Binocular retinal scanning laser display with integrated focus cues for ocular accommodation. 2003. DOI:10.1117/12.474135.

[145] Martijn J Schuemie et al. “Research on presence in virtual reality: A survey”. In: CyberPsychology & Behavior 4.2 (2001), pp. 183–201.

[146] Bernd Schwald and Blandine De Laval. “An augmented reality system for training and assistance to maintenance in the industrial context”. In: (2003).

[147] Frank Schwierz. “Graphene transistors”. In: Nature nanotechnology 5.7 (2010), pp. 487–496.

[148] J Servan et al. “Assembly work instruction deployment using augmented reality”. In: Key Engineering Materials. Vol. 502. Trans Tech Publ. 2012, pp. 25–30.

[149] Abhishek Seth, Judy M Vance, and James H Oliver. “Virtual reality for assembly methods prototyping: a review”. In: Virtual reality 15.1 (2011), pp. 5–20.

[150] Neal E Seymour et al. “Virtual reality training improves operating room performance: results of a randomized, double-blinded study”. In: Annals of surgery 236.4 (2002), pp. 458–464.
[151] Shahnaz Shahrbanian et al. “Scientific evidence for the effectiveness of virtual reality for pain reduction in adults with acute or chronic pain”. In: Stud Health Technol Inform 144 (2009), pp. 40–43.

[152] Linda Shapiro. Lecture notes from CSE455: Computer Vision, Department of Computer Science & Engineering, University of Washington. 2009.

[153] Mai El-Shehaly et al. “A VR based intervention tool for autism spectrum disorder”. In: Proceedings of the 18th International Conference on 3D Web Technology. ACM. 2013, pp. 216–216.

[154] Stephen M Smith and J Michael Brady. “SUSAN—A new approach to low level image processing”. In: International journal of computer vision 23.1 (1997), pp. 45–78.

[155] Ivan E. Sutherland. “A Head-mounted Three Dimensional Display”. In: Proceedings of the December 9-11, 1968, Fall Joint Computer Conference, Part I. AFIPS ‘68 (Fall, part I). San Francisco, California: ACM, 1968, pp. 757–764. DOI: 10.1145/1476589.1476686

[156] Mike Taulty. Windows 10, UWP and Sphero—Bringing 2D UWP Demo Code to HoloLens. URL: https://mtaulty.com/2016/12/14/windows-10-uwp-and-sphero-bringing-2d-uwp-demo-code-to-hololens/.

[157] Henry E. Lowood for The Encyclopedia Britannica. Virtual reality (VR). URL: https://www.britannica.com/technology/virtual-reality#ref884322.

[158] CuriousInventor (YouTube user). How the Kinect Depth Sensor Works in 2 Minutes. 2013. URL: https://www.youtube.com/watch?v=uq9SEJxZiUg.

[159] Vassilios Vlahakis et al. “Archeoguide: first results of an augmented reality, mobile computing system in cultural heritage sites”. In: Virtual Reality, Archeology, and Cultural Heritage 9 (2001).

[160] G. Welch and E. Foxlin. “Motion tracking: no silver bullet, but a respectable arsenal”. In: IEEE Computer Graphics and Applications 22.6 (Nov. 2002), pp. 24–38. ISSN: 0272-1716.

[161] Giles Westerfield, Antonija Mitrovic, and Mark Billinghurst. “Intelligent augmented reality training for assembly tasks”. In: International Conference on Artificial Intelligence in Education. Springer. 2013, pp. 542–551.

[162] Giles Westerfield, Antonija Mitrovic, and Mark Billinghurst. “Intelligent augmented reality training for motherboard assembly”. In: International Journal of Artificial Intelligence in Education 25.1 (2015), pp. 157–172.

[163] Z Xu et al. “A virtual reality based fire training simulator with smoke hazard assessment capacity”. In: Advances in engineering software 68 (2014), pp. 1–8.
[164] rvdm88 (YouTube user). *HTC Vive Lighthouse Chaperone tracking system Explained*. URL: https://www.youtube.com/watch?v=J54dotTt7k0

[165] Z Yovcheva, D Buhalis, and C Gatzidis. *Overview of smartphone augmented reality applications for tourism. e-Review of Tourism Research (eRTR), 10 (2), 63–66. 2012.*