Preface

"Virtual reality", a strange oxymoron, is back in common use in the media, like in the early 1990s, a quarter of a century ago! A period that today's young innovators are not very familiar with. Yes, at the risk of shocking some people, we must reveal that this science and the associated techniques are no invention of the 21st Century but date back well into the previous century!

Today, we are witnessing the renaissance and democratization of virtual reality, with its share of relevant and effective applications, as well as a host of technological difficulties that no developer can afford to ignore. Some enthusiasts wish to create new applications and believe that skills in innovation are all that is required. However, this approach is doomed to failure unless it is preceded by a detailed study of the state of the art of virtual reality techniques and a knowledge of the fundamentals and existing uses. Many young entrepreneurs have contacted me, thinking they have a novel virtual reality application when they don't even have a basic understanding of this science or its techniques. I have had to tell others, "but this already exists in the industry, it is already being marked by companies that are over twenty years old". The latest innovation, the "low-cost" visioheadset or immersive headset, may have sparked off a mad buzz in the media, but the field of virtual reality has existed long before this! 2016 was not 1 V.R. (the first year of our science, Virtual Reality)! However, the considerable decrease in the price of visioheadsets has made it possible to open this technology up to large-scale use. The media and websites dedicated to virtual reality are most often run by non-specialists and are abound with indiscriminately proposed applications: some of these have existed for several years now, and others, while useful, would be inappropriate or even crazy. Virtual reality is not a magic wand. Let us remember that it is not sufficient to use an innovative technology for its own sake. This innovation must be made functional for the user, using new technological devices, whether a visioheadset or any other equipment.

Research and development in virtual reality has been undertaken for more than a quarter of a century by the VR community in France and in other parts of the world. It would be a great misfortune to be unaware of this work. However, if you are reading this now, then you have made the right choice! The fruit of all the research and professional developments in the field over the past decade is now presented in this volume. And who better than Bruno Arnaldi, Pascal Guitton and Guillaume Moreau to guide you through this arduous journey through the past 10 years in R&D in virtual development, as well as to give a glimpse of what the future may hold?

The three editors of this book are major actors in the field of virtual reality and augmented reality. All of them have participated in developing research in France, via the Groupe de Travail GT-RV (GT-VR Work Group) at CNRS (1994) and then through the Association Française de Réalité Virtuelle (The French Virtual Reality Association), which they established in 2005 as co-founders and in which they are very active members: President, Vice-President or members of the administrative council. This association has made it possible to efficiently structure the entire community (teachers, researchers, industrialists and solution providers). In parallel to this, thanks to their enthusiastic and indispensable support, I was able to organize and edit a collective work with contributions from more than a hundred authors, over five volumes: the *Virtual Reality Treatise*. There were three coordinators in this project. However, the third edition of this book is now 10 years old, and we needed a more recent publication to step into the breach.

It is essential to have a strong basic knowledge of virtual reality before plunging into the field, whether you are a student or an entrepreneur. The contents of this book, to which 30 authors have contributed, cover all the current problems and research questions, as well as the commercially available solutions: the immersion of a user, the user's interfacing with the artificial space and the creation of this artificial space. All the technology and software available today are discussed here. The human factor is also taken into account, and there is a detailed description of methods of evaluation.

There is also a section devoted to the risks associated with the use of visioheadsets.

A recent community that has come up in France, under the Think Tank UNI-VR, is bringing together professionals from the world of movies and audiovisual material. Using new 360° cameras, which enable the creation of artificial worlds made out of 360 images and not synthetic images, this group aims to create a new art, with two complementary approaches: one that produces "360 videos", where the user remains a spectator, but with a bodily and proprioceptive immersion in the 360° video; the other designs "VR videos", where the user becomes a "spect-actor", as if they are able to interact with the story that unfolds the characters and the artificial environment, this being the authentic field of virtual reality. This artistic goal is close to that of "interactive digital arts", even though these two communities do not know much about each other. Towards the end of the 1980s, French and international artists in the digital arts appropriated virtual reality to create interactive artistic creations, ("les pissenlits" (The Dandelions) by E. Couchot, M. Bret and M-H. Tramus, 1988; "L'autre" (The Other) by Catherine Ikam, 1991). A journalist from "Les Cahiers du Cinéma" once interviewed me, stating that "virtual reality is the future of the movies!" A strange remark, when we know of the antagonism between the movies (where the spectator is passive) and virtual reality (where the user is active, interacting with the artificial environment)! Another journalist was carried away by an innovation without bothering to learn about the fundamentals of this innovation and its impact on the individual! However, like all specialists, I did not imagine that 20 years later 360° would also enable the creation of an artificial world, where a user could be immersed in the heart of a film. By allowing the user to interact here, we enter into the field of virtual reality or augmented reality, by blending the real world and the artificial space. Unlike cinema, here there is no longer "a story to be told" but "a story to be lived". With this book, readers have a source of detailed information that will allow them to successfully develop their own "VR videos".

However, the digital modeling of an artificial world and its visual representation through synthetic images will remain the chief avenue for the development of the uses of virtual reality. For at least 15 years now, professional applications (e.g. industrial and architectural designs, training and learning, health) have made use of this. Different communities must collaborate more closely on theorizing this discipline and its techniques, which are exhaustively presented in this book by Bruno Arnaldi, Pascal Guitton and Guillaume Moreau. The merits of this book cannot be overstated – they must be bought!

Philippe FUCHS
January 2018

Introduction

It can have escaped no one that 2016 and 2017 often features in the media as “The Time” for virtual reality and augmented reality. It is no less obvious that in the field of technology, many and regular breakthroughs are announced, each more impressive than the last. In the face of this media clamor, it is useful to step back and take a pragmatic look at some historical facts and information:

– The first of these is the fact (however difficult to accept) that virtual reality and augmented reality date back several decades and that there is a large international community working on these subjects. This work is being carried out both at the scientific level (research teams, discoveries, conferences, publication) and at the industrial level (companies, products, large-scale production). It is also useful to remember that many companies, technological or not, have been successfully using virtual reality and augmented reality technologies for many years now.

– Many of these technological announcements talk about the design of “new” virtual reality headsets (e.g. HTC Vive, Oculus Rift) and augmented reality headsets (e.g. HoloLens). But the fact is that the invention of the first “visioheadset”[1] dates back to almost 50 years, to Ivan Sutherland’s seminal work [SUT 68].

– Let us also note that these “visioheadsets” only represent a small part of the equipment used in virtual reality, whether for display (with projection systems, for example), motion-capture or interaction.

Introduction written by Bruno ARNALDI, Pascal GUITTON and Guillaume MOREAU.

1 This is what we will call these gadgets in this book. The reason for this will be made clear later.

– The concept and applications of virtual reality are described in the series *Le traité de la réalité virtuelle* (The Virtual Reality Treatise), an encyclopedic volume produced collectively by many French authors (both academics and voices from the industry), the breadth and scope of which remains unmatched even today. The different editions of this are:

- the first edition in 2001 (Presses de l'Ecole des Mines), written by Philippe Fuchs, Guillaume Moreau and Jean-Paul Papin with 530 pages;

- the second edition in 2003 (Presses de l'Ecole des Mines), edited by Philippe Fuchs and Guillaume Moreau with help from 18 contributors, running to 930 pages in 2 volumes;

- the third edition in 2005 (Presses de l'Ecole des Mines), edited by Philippe Fuchs and Guillaume Moreau, with over 100 contributors, running to 2,200 pages in 5 volumes;

- an English version "Virtual Reality: Concepts and Technologies", in 2011 (CRC Press), edited by Philippe Fuchs, Guillaume Moreau and Pascal Guitton with 432 pages.

– Finally, we must mention the creation of the "Association Française de Réalité Virtuelle" (AFRV) or the French Virtual Reality Association, established in 2005. The association has made it possible to structure the community better by bringing together teachers and researchers from universities and research institutions as well as engineers working within companies. From 2005 onward, the AFRV has been organizing an annual conference that sees presentations, activities and exchanges among participants.

As can be seen from this overview, there are already several communities at the international level as well as a wealth of literature on the subject and anyone who wishes to establish a scientific and/or technological culture will benefit from referring to publications such as [FUC 16] (in French) or [LAV 17, SCH 16], to mention a few.

I.1. The origins of virtual reality

When we talk about historic references relating to virtual reality, we may commence by discussing Plato's Allegory of the Cave [PLA 07]. In Book VII of Plato's Republic, there is a detailed description of the experiences of several men chained in a cave, who can only perceive shadows (thrown against the walls of the cave) of what happens in the outside world. The notion of reality and perception through what is and what is perceived becomes the subject of analysis, in particular concerning the passage from one world to another.

A few centuries later, in 1420, the Italian engineer Giovani Fontana wrote a book, *Bellicorum instrumentorum liber* [FON 20], in which he describes a magic lantern capable of projecting images onto the walls of a room (see Figure I.1(a)). He proposed that this could be used to project the images of fantastic creatures. This mechanism brings to mind the large immersion system (CAVE) developed a few centuries later by Carolina Cruz-Neira *et al.* [CRU 92] at the University of Illinois.

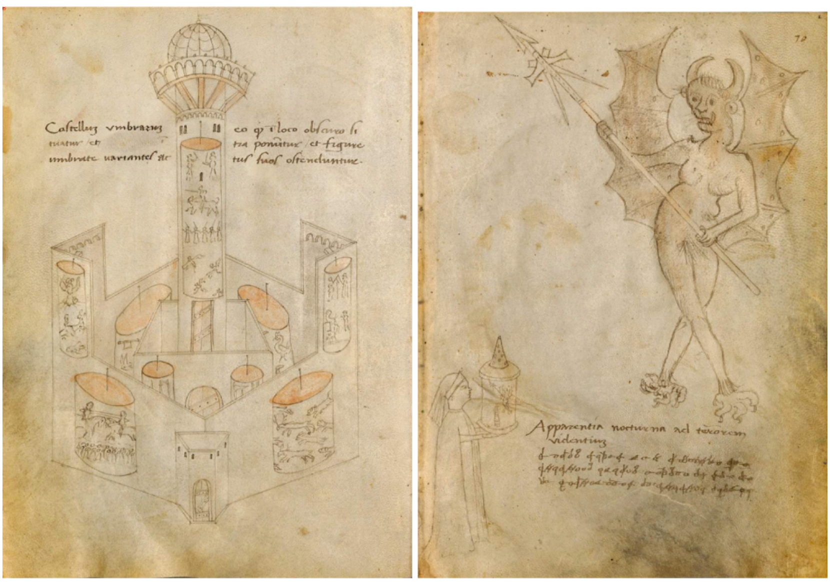

Figure I.1. *a) Diagram of Giovani Fontana's magic lantern, b) using the magic lantern. For a color version of this figure, see www.iste.co.uk/arnaldi/virtual.zip*

In books that recount the history of VR, we often come across the (legitimate) controversy around the first appearance of the term "virtual reality". Some authors attribute it to Jaron Lanier, during a press conference in 1985, while others attribute it to Antonin Artaud, in his 1983 essay, *Le* *théâtre et son double* (published in English as “The Theatre and its Double”) [ART 09].

Artaud was unarguably the inventor of this term, which he used in his collection of essays on Theatre and, more specifically, in the chapter titled *Le théâtre alchimique* (“The Alchemical Theatre”). It must be noted that in this volume, Artaud talks at length about reality and virtuality (these words being frequently used in the text). The precise citation where the term “virtual reality” appears is on page 75 of the 1985 edition, collection Folio/essais de Gallimard:

> “All true alchemists know that the alchemical symbol is a mirage as the theater is a mirage. And this perpetual allusion to the materials and the principle of the theater found in almost all alchemical books should be understood as the expression of an identity (of which alchemists are extremely aware) existing between the world in which the characters, objects, images and in a general way all that constitutes the *virtual reality* of the theater develop and the purely fictitious and illusory world in which the symbols of alchemy are evolved”.

Furthermore, a few pages earlier, he speaks about Plato’s Allegory of the Cave.

However, it is clear that Jaron Lanier was the first person to use this term in the sense that it is used in this book, when he used the English term *virtual reality*. It is also useful to remember that there is a subtle difference between the English term *virtual* and the French word *virtuel* (see Chapter 1, Volume 1 of the *Virtual Reality Treatise*, edition 3). In English, the word means “acting as” or “almost a particular thing or quality”. However, in French, the word indicates “potential”, what is “possible” and what “does not come to pass”. Linguistically speaking, the more appropriate French term would have been “réalité vicariante” – a reality that substitutes or replaces another.

Science-fiction writers, especially those writing in the “speculative fiction” genre (a genre which, as its name indicates, consists of imagining what our world could be like in the future) have also written books that integrate and/or imagine the VR-AR technologies we will discuss in this volume. The list of such books is quite long, and the four books presented here have been chosen simply for the impact they had. In chronological order, these are:

– Vernor Vinge, in his 1981 novella *True Names*, introduced a cyberspace (without explicitly naming it thus), where a group of computer pirates use virtual reality immersion technology to fight against the government. He is also the creator of the concept of "singularity": that point in time when machines will be more intelligent than human beings;

– William Gibson, in his 1984 novel *Neuromancer*, described a world of networks where virtual reality consoles allow a user to live out experiences in virtual worlds. Gibson "invented" the term cyberspace, which he described as "a consensual hallucination experienced daily by billions of legitimate operators". This concept of cyperspace spans different worlds: the digital world, the cybernetic world and the space in which we evolve;

– Neal Stephenson, in his 1992 novel *Snow Crash*, introduced the concept of the metaverse (a virtual, thus fictional, world in which a community, represented by avatars, is evolving); a universe like the one in the online virtual world *Second Life*;

– Ernest Cline, in his 2011 novel *Ready Player One*, offerred us a world where humanity lives in an enormous virtual social network to escape the slums in real life. This network also contains the key to riches, leading to a new kind of quest for the holy grail.

Literature is not the only field in which early references to virtual reality set up links between the real and the virtual. For example, we must mention the pioneering work of Morton Leonard Heilig in the world of cinema. Following a project he had worked on since the 1950s, he patented the *Sensorama* system in 1962. This system allowed users to virtually navigate an urban setting on a motorbike, in an immersive experience based on stereoscopic visualization, the sounds of the motorbike and by reproducing the vibration of the engine and the sensation of wind against rider's face.

Cinema has made use of the emergence of new technologies quite naturally. In 1992, Brett Leonard directed *The Lawnmower Man*, starring Pierce Brosnan as a man who is the subject of scientific experiments based on virtual reality (see Figure I.2). Unsurprisingly, the story revolves around some of the undesirable effects. An interesting point about this film is that during shooting, actors used real equipment from the VPL Research company, set up by Jaron Lanier (who had already filed for bankruptcy by this time). Of course, no one can forget the 1999 film *The Matrix*, the first film in the Matrix trilogy, directed by Les Wachowski, starring Keanu Reeves and Laurence Fishburne. The plot is centered on frequent journeys between the real and the virtual worlds, the hero's duty being to liberate humans from the rule of the machines by taking control of the matrix. The technology in this film is much more evolved as there is total immersion, and it is so credible that the user has a few clues to tell whether he is in the real or the virtual world. Another cult film, oriented more towards human–machine interaction (HMI) than VR itself, was Steven Spielberg's 2002 film *Minority Report*, starring Tom Cruise (see Figure I.3). This film describes an innovative technology that allows a person to interact naturally with data (which would serve as inspiration for many future research projects in real labs). These three films are certainly not the only ones that talk about VR – a great many others could be named here; however, these three are iconic in this field.

Figure I.2. *A still from the movie* The Lawnmower Man

Figure I.3. *A still from the movie* Minority Report

After having discussed the mention of VR-AR in different fields of art, it is also interesting to analyze how this technology is used in these contexts. Cinema will become an intensive user of VR through the use of 360° cinema, for instance (and on the condition that the spectator finally becomes the spect-actor). In the artistic world, we have to work on the codes and rules for cinematographic writing that these new operational modes will bring about. In particular, in traditional cinema, the narration is constructed on the principle that the director, through their frames, will almost "lead the spectator by hand" to the point from which they want the spectator to view a particular scenic element. In a context where the spectator can freely create their own point of view, artistic construction does not remain the same. If we add to this the fact that the user has the ability to interact with their environment and therefore modify elements in the scene, the narrative complexity deepens and begins to approach the narrative mechanisms used in video games. Combining real and digital images (mixed reality) is another path for development and study, which will emerge soon.

The world of comic books/graphic novels is also influenced either through the development of immersion projects (e.g. *Magnétique*, by Studio Oniride in 2016; http://www.oniride.com/magnetique/) or through using VR in the world of a comic series as is the case with *S.E.N.S*, a project co-produced by Arte

France and Red Corner studio in 2016, inspired by the work of Marc-Antoine Mathieu (see Figure I.4). Indeed, as the universe in VR experiences is not necessarily a reproduction of a real world, it could also be the fruit of pure fantasy and a comic book world lends itself readily to such experimentation.

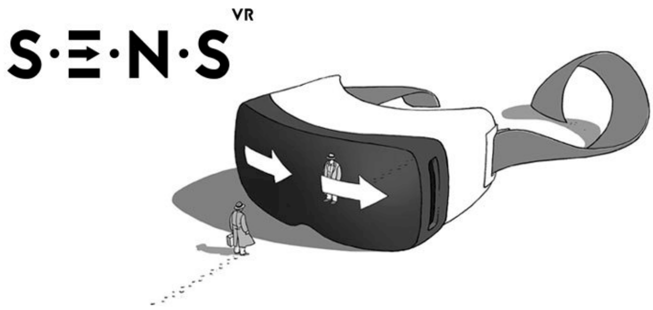

Figure I.4. *Projet* S.E.N.S

I.2. Introduction to the basic concepts

This section aims to briefly describe the fields of VR and AR. We will review the principal concepts for each and provide some definitions[2] in order to clearly define the scope of this book. Readers who seek more information on this are invited to consult the *Virtual Reality Treatise* [FUC 05].

I.2.1. *Virtual reality*

We will first and foremost remind ourselves that the objective of VR is to allow the user to virtually execute a task while believing that they are executing it in the real world. To generate this sensation, the technology must "deceive the brain" by providing it with information identical to the information the brain would perceive in the real environment.

Let us take an example that we will use for the rest of this section: you have always dreamed of flying a private aircraft without ever having acted on this

2 Several different definitions can be found in other books; those that we have chosen here are brief and correspond to a general consensus.

desire. Well then, a VR system could help you to (virtually) realize this dream, by simulating the experience of flying the plane. To start with, it is essential that you are given synthetic images that reproduce the view from a cockpit, the runway first and then an aerial view of the territory you will fly over. In order to give you the impression of "being in the plane", these images must be large and of good quality, so that the perception of your real environment is pushed to the background or even completely replaced by that of the virtual environment (VE). This phenomenon of modifying perception, called *immersion*, is the first fundamental principle of VR. VR headsets, which will be called *visioheadsets* in this book, offer a good immersion experience as the only visual information perceived is delivered through this device.

If the system also generates the sound of the aircraft engine, your immersion will be greater as your brain will perceive this information rather than the real sounds in your environment, which then reinforces the impression of being in an aircraft. In a manner similar to that of the visioheadset, an audio headset is used, as it can insulate against ambient noise.

A real pilot acts in the real environment by using a joystick and dials to steer the plane. It is absolutely indispensable that these actions be reproduced in the VR experience if we wish to simulate reality. Thus, the system must provide several buttons to control the behavior of the aircraft and a joystick to steer it. This *interaction* mechanism between the user and the system is the second fundamental principle of VR. It also serves to differentiate VR from applications that offer good immersion but no real interaction. For example, movie theaters can offer visual and auditory sensations of very high quality, but the spectator is offered absolutely no interaction with the story unfolding on the screen. The same observation can be made for "VR-videos", which have recently become quite popular, but the only interaction offered is a change in point of view (360°). While this family of applications cannot be challenged, they do not qualify as VR experiences as the user is only a spectator and not an actor in the experience.

Let us return to our earlier example: in order to reproduce reality as closely as possible, we must be able to steer the aircraft using a force-feedback joystick, which will generate forces in order to simulate the resistance experienced when using a real joystick, which can be due to air resistance, for example. This haptic information significantly reinforces the user's immersion in the VE. Moving further towards faithfully reproducing reality, let us imagine that we can provide a real aircraft cockpit fitted with real seats and control apparatus and that we can perfectly adapt the external screens so as to ensure that the synthetic images appear naturally in the windows and the windscreen of the aircraft. The impression is then even better as we give our brain additional visual impressions (the components of the cockpit), auditory information (the sound of the buttons being clicked or pressed) and haptic feedback (the feeling of being seated in the airplane seat). This type of a device will, undoubtedly, convince any brain that it is really seated in a cockpit, piloting an aircraft. And of course, these devices *do* exist in reality: these are the aircraft simulators that have been in use for many years, used first to train military pilots and then commercial pilots, and available today as entertainment devices for non-pilots who want to feel like they are flying a plane.

On the basis of this example, we can define VR as the capacity given to one (or more) user(s) to carry out a set of real tasks in a virtual environment, this simulation being based on the immersion of a user in this virtual environment through the use of interactive feedback from and interaction with the system.

Some remarks on this definition:

– "Real tasks": in effect, even though the task is carried out in a VE, it is real. For example, you could start learning to fly a plane in a simulator (as real pilots actually do) because you are developing the skills that will then be used in a real aeroplane.

– "Feedback": this is sensory information (e.g. visual, auditory, haptic) that the computer synthesizes using digital models, that is, descriptions of the form and appearance of an object, the intensity of a sound or of a force.

– "Interactive feedback": these synthetic operations result from relatively complex software processing, and this therefore takes a certain amount of time. If this duration is too long, then our brain perceives the display of a fixed image, then another, destroying any sense of visual continuity and therefore of movement. It is consequently imperative that the feedback is interactive – imperceptible – to obtain a good immersion experience.

– "Interaction": this term designates the functionalities offered to the user to act on the behavior of the system, by moving round, manipulating and/or displacing objects in VE; and in a symmetric manner, the information that is then delivered by the VE to the user, whether visual, auditory or haptic. Let us note that if there is no interaction, then we cannot refer to the experience as VR.

Generally speaking, why do we use VR? This technology was developed to achieve several objectives:

– *Design*: engineers have used VR for a long time, in order to improve the construction of a building or a vehicle, either for moving around within or around these objects or using them virtually in order to detect any design flaws there may be. These tests, which were once carried out using models of increasing complexity, up to a scale 1, were progressively replaced by VR experiences, which are less expensive and can be produced more quickly. It must be noted that these virtual design operations have been extended to contexts beyond tangible objects, for example, for movements (surgical, industrial, sports) or complex protocols.

– *Learning*: as we have seen in our example above, it is possible, today, to learn to pilot any kind of vehicle: plane, car (including F1 cars), ship, space shuttle or spaceship, etc. VR offers many advantages, the first and foremost being that of safety while learning. There is also an ease of replication and the possibility of intervening in the pedagogic scenario (simulating the breakdown of a vehicle or a weather event). Let us note that these learning operations have extended beyond steering vehicles to more complex processes such as the management of a factory or a nuclear center from a control room, or even learning to overcome phobias (of animals, empty spaces, crowds, etc.) using behavioral therapy that is based on VR.

– *Comprehension*: VR can offer learning supports through the interactive feedback it provides (especially visual), in order to better understand certain complex phenomena. This complexity can result from a difficulty or even an impossibility in accessing information on the subject as this information may no longer exist, may be difficult to access (underground or underwater, for oil prospecting; or it may be the surface of a planet that we wish to study), may be too voluminous for our brain to take in (big data) or may be imperceptible to the human senses (temperature, radioactivity). In many contexts, we seek this deeper understanding in order to enable better decision-making: where do we drill for oil? What financial action must we carry out? And so on.

To conclude, it is important to note that very precise and formal definitions for VR exist. For example, in Chapter 1 of Volume 1 (which presents the fundamental principles of the domain) of the *Virtual Reality Treatise* [FUC 05], we find this definition: “virtual reality is a scientific and technical field that uses computer science and behavioral interfaces in order to simulate, in a virtual world, the behavior of 3D entities that interact with each other in real time and with one or more users immersed in a pseudo-natural manner through sensorimotor channels”.

I.2.2. *Augmented reality*

The goal of AR is to enrich the perception and knowledge of a real environment by adding digital information relating to this environment. This information is most often visual, sometimes auditory and is rarely haptic. In most AR applications, the user visualizes synthetic images through glasses, headsets, video projectors or even through mobile phones/tablets. The distinction between these devices is based on the superimposition of information onto natural vision that the first three types of devices offer, while the fourth only offers remote viewing, which leads certain authors to exclude it from the field of AR.

To illustrate this, let us use the example of a user who wishes to build a house. While they will only have blueprints, initially, AR will allow them to move around the plot, visualize the future building (by overlaying synthetic images onto their natural vision of the real environment) and perceive general volumes and the implantation in the landscape. As they move on to the process of construction, the user can compare several design and/or furnishing possibilities by visualizing painted walls or furniture arranged in different layouts in a structure that is still under construction. Going beyond interior design and furnishing, it is also possible for an electrician to visualize the placement of insulation and for a plumber to visualize the placement of pipes, even though these are to be hidden behind concrete screeds or concealed in a wall. In addition to placement, the electrician can also see the diameters used and thus the strength of the current being transported, and the plumber can visualize the color and thus the temperature of the water being supplied.

Why develop AR applications? There are several important reasons:

– *Driving assistance*: originally intended to help fighter jet pilots by displaying crucial information on the cockpit screen so that they would not need to look away from the sky to look at dials or displays (which can/could have been be crucial in combat), AR gradually opened up the option of assisted driving to other vehicles (civil aircraft, cars, bikes) including navigation information such as GPS.

– *Tourism*: by enhancing the capabilities of the audio-guides available to visitors of monuments and museums[3], certain sites offer applications that combine images and sound.

– *Professional gesture assistance*: in order to guide certain professional users in their activities, AR can allow additional information to be overlaid onto their vision of the real environment. This information may not be visible in the real environment, as it is often "buried". Thus, a surgeon may operate with greater certainty, by visualizing the blood vessels or anatomical structures that are invisible to them, or a worker participating in constructing an aeroplane may visually superimpose a drilling diagram directly onto the fuselage, without having to take measurements themselves, which leads them to gain speed, precision and reliability.

– *Games*: while it was popularized by *Pokémon Go* in 2016, AR made inroads into this field a long time ago, through the use of augmented versions of games such as *Morpion*, *PacMan* or *Quake*. It is clear that this sector will see a lot more development based on this technology, which will make it possible to combine the real environment and fictional adventures.

Even though they share algorithms and technologies, VR and AR can be clearly distinguished from each other. The main difference is that in VR the tasks executed remain virtual, whereas in AR they are real. For example, the virtual aircraft that you piloted never really took off and thus never produced CO2 in the real world, but the electrician using AR may cut through a gypsum board partition to install a real switch that can turn on or off a real light.

3 These can be considered to belong to the field of AR, as they offer visitors auditory information that enhances their knowledge of the real environment.

As regards AR, compact definitions have been proposed by many scientists. For example, in 1997, Ronald T. Azuma defined AR as a collection of applications that verify the following three properties [AZU 97]:

1) a combination of the real and the virtual;

2) real-time interaction;

3) integration of the real and the virtual (e.g. recalibration, obstruction, brightness).

I.3. The emergence of virtual reality

I.3.1. *A brief history*

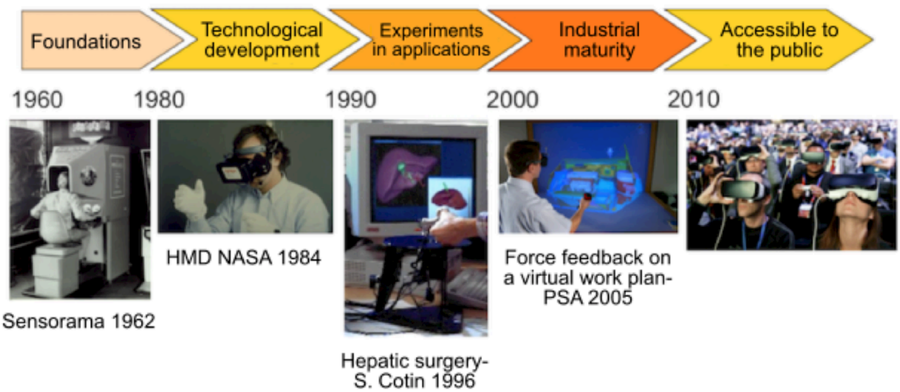

Figure I.5. *Evolution of the field of virtual reality. For a color version of this figure, see www.iste.co.uk/arnaldi/virtual.zip*

Another analysis of the state of virtual reality today allows us to draw a timeline for the stages in the evolution of this field (see Figure I.5). The broad stages of evolution are:

– *before 1960 – the foundations*: numerous approaches and methods (used even today in virtual reality) were perfected well before the birth of "virtual reality" as a field. We have the first representations of reality through paintings (pre-historic), perspectives (Renaissance), panoramic displays (18th Century), stereoscopic vision and cinema (19th Century) and the British pilot training flight-simulators from World War II. Finally, we have the very notion of immersion, the heart of virtual reality, which was used by Morton Heilig from 1956 onwards in his *Sensorama*, with its multimodal feedback, and in 1969 with his *Experience Theater*, the precursor to all large-screen dynamic movie theaters.

– *1960–1980 – the first steps*: the emergence of computer sciences enabled the development of all the elementary components that would then lead to the advent of virtual reality. Components used in the synthetic images that, even today, represent virtual environments are the modeling and manipulation of 3D objects, rendering algorithms (above all, the Z-buffer algorithm [CAT 74]) and the treatment of light and lighting models [GOU 71, PHO 75]. Components for interaction between the user and the system, were Sketchpad [SUT 63], the first visioheadset (or head-mounted display, abbreviated to HMD) [SUT 68] or the GROPE system, the first work carried out on force feedback (initiated in 1971 at the University of North Carolina by Frederick Brooks), which formed the basis for haptic feedback. On the application front, developments around flight simulators progressed rapidly, for instance, within the VITAL and VCASS projects carried out by the United States Air Force.

– *1980–1990 – technological development*: this stage was characterized by the development of technology specific to 3D interaction, in particular. In 1985, Michael McGreevy and Scott Fish (NASA Ames Research) rediscovered the virtual reality display system and gave it the name by which it was known forevermore – HMD: head-mounted display [FIS 87]. In 1986, Scott Fisher proposed spatialized sound restitution. Jaron Lanier (an American) and Jean-Jacques Grimaud (a Frenchman) established the company VPL Research, which sold the first virtual reality applications, using their Data Glove coupled with a visioheadset that it had designed. Incidentally, in 1987, Jaron Lanier "invented" the term *virtual reality*. Thanks to the progress in computer equipment, Frederick Brooks' GROPE system became operational with the manipulation of molecules close to 1,500 atoms ([BRO 90].

– *1990–2000 – experiments in application*: this is the decade in which the integration of material and software solutions made it possible to implement experimental applications that were credible and operational. Let us begin with the video game industry, which was one of the first to foresee the potential benefits of virtual reality and to offer innovative solutions using equipment that was specifically developed for this use: Virtuality (1991), Sega VR (1993), Virtual Boy (1995) and VFXA Headgear, a range of products that, 20 years later, still influence present-day solutions. Industries related to transport (automobile, aeronautic, aerospace, maritime) first used virtual reality to design vehicles and then to learn how to drive them. The medical sector also saw some experimentation using VR in this period. For example, Hunter Hoffman and his colleagues used virtual reality to reduce pain perception among patients who had suffered severe burns at the University of Washington Harborview Burn Center, and Stéphane Cotin *et al.* proposed a complete simulation system for hepatic surgery with force feedback [COT 96]. The field of energy and especially the oil industry also had an early understanding of the value of and return on investment possible using these new technologies.

– 2000–2010 – industrial maturity: after having focused on product-design and learning how to drive vehicles, the applications of VR evolved towards maintenance and training, using simulation to control industrial processes (monitoring a factory from a command room, for example).

We can also see the increase in the number of applications that use VR to better understand an environmental phenomenon, especially to better decide how to proceed. Let us take the case of the petroleum industry, which studies subsoils in order to optimize the placement of drilling wells, or even the world of finance, where spaces composed of share revenues and growth curves are visually studied in order to better decide what actions to take (buying, selling). The goal of better understanding for better decision-making can also be seen in product-design, during project reviews, which reduces or even eliminates the need for physical models.

As regards equipment, the dawn of this decade saw significant progress in the installation of immersive rooms (CAVE and, above all, the SGI Reality Center) in both the academic world and (large) companies. Users can also easily find capture, localization and orientation equipment, such as the force-feedback arm (haptic feedback).

Last, but certainly not least, this period saw a very noticeable evolution in the development of VR applications: alongside the techno-centric approach adopted by the pioneers in the field, there arose an anthropocentric approach. This change was due to two factors playing out simultaneously:

- the increasing diffusion of VR led researchers in the social sciences, mainly in the cognitive sciences, to study this new paradigm. This opened up fields of reflection that were unknown until then;

- application developers, noticing the rejection of some uses as well as the discomfort that certain users experienced, began looking for solutions that were not just purely technological.

A new fashion of thinking about applications, which would take into account the human factor, emerged from the convergence between the knowledge and results obtained by researchers and the needs of the developers, and this approach continues to be used today.

– *2010 onward – deployment towards the larger public*: this last period was marked by the arrival of new equipment at costs that were much lower than those of earlier devices, while also offering a high level of performance. This rebound is largely due to the development of smart phones as well as that of video games. Even though visioheadsets have been publicized the most in the media (e.g. Oculus Rift, HTC Vive), new motion-capture systems have also emerged. This explosion has resulted in numerous articles being published in the general media, bringing information about these technologies to a wider public: first addressing professionals in companies that were smaller than the large groups that worked on designing new uses for VR-AR, and then relaying information directly to the general public, which was entranced by the announcements (even those that were completely unrealistic) and grew interested in the possibilities offered by various sectors.

In parallel to this new equipment, which was just the tip of the iceberg, new software environments established themselves, often arising from the world of video games (such as Unity 3D). This made it possible for "new" developers, from the above-mentioned SMEs, to independently develop their solutions.

It is clear that this is just the beginning of VR-AR becoming accessible to the general public; after a phase of media uproar, the true benefits will emerge and there is no doubt that the coming years will witness an explosion in the mass use of these technologies.

Given these facts, which by no means constitute an exhaustive history of the field, our book aims to answer the following question: *what has happened over the last 10 years?* (this period corresponds to the time since the publication of the last edition of the *Virtual Reality Treatise*). Before providing an extensive description of notable events in the evolution of the field over the last decade, and in order to understand *what* has truly changed, it will be useful to study the evolution of the socio-economic context.

Indeed, 10 years ago, the landscape consisted of:

– research laboratories that develop fundamental methods and technologies;

– large industrial entities, often manufacturing industries or industries depending on large infrastructure that make use of technologies (e.g. in France: PSA, Renault, Airbus, SNCF, etc.);

– a few technological startups that proposed software tools and (often experimental) equipment, for example Haption, Virtools and Laster.

The manufacture of products was often realized thanks to collaboration between these three categories of actors in ambitious projects. Professional integrated software solutions were quite a heavy burden, both for the application developer and for the end-user.

I.3.2. *A revolution among actors*

In the last decade, there have been several profound transformations in this landscape.

– First of all, there have been some startups that have had real commercial success with their innovations:

- Oculus Rift (2013[4]), which was bought by Facebook, resulting in a massive diffusion of the products;

- Leap Motion and its lightweight position sensors (2013).

– And then there are large organizations with considerable resources in terms of capital and development teams that have now stepped in and taken an interest in these technologies, whether in designing them or buying them from existing actors. For example:

– These companies offer the following products:

- the Microsoft Kinect sensor (2010);

4 The dates mentioned here correspond to their diffusion in France; they may thus differ from the start dates for the projects or the announcement dates.

- Google Glass (2013) (even though this was not a commercial success, it saw significant distribution);

- Samsung Gear VR headset (2015);

- Microsoft HoloLens headset (2016);

- Sony PS-VR headset (2016);

- HTC Valve Vive headset (2016);

- development kit for the Apple smart phone range. Apple acquired Metaio, a well-established actor in the field of Augmented Reality (2017).

I.3.3. *Technological revolution*

Both on the material and software plane, this decade has been rich in breakthrough new products:

– In the field of software, we must note the availability of professional integrated software solutions that are available for free, allowing anyone with the know-how to develop their own solutions:

- the release of the first free version of Unity 3D in October 2009;

- the release of Apple's ARKit in 2017.

– Another point that became a determining factor in the democratization of technology and its uses was the evolution of terminals. In effect, in June 2007, Apple sold its first iPhone, and everyone knows the impact that this had on the mobile telephone market, as well as on the general field of mobile applications. This evolution rapidly led to users having access to a terminal equipped with a high-quality screen, coupled with a camera and several sensors (e.g. accelerometers, tactile screen). It was a short step from here to giving the average user access to mobile VR or AR applications, which had, hitherto, been unknown or too expensive. Nonetheless, we must note that, of the number of mobile applications claiming to be VR or AR applications, very few actually bring either AR or VR into play and most are rather counterproductive to the development of these technologies. The advent of tablets also led to the development of VR and AR by removing an important limiting factor in the mobile phones: screen size.

– Finally, video games have been majorly pushed as well as recent progress in the field of visioheadsets (virtual reality and augmented reality headsets), which have allowed for a massive democratization of these technologies, mainly as a result of very low acquisition costs as compared to earlier equipment, with a quality that is perfectly satisfactory.

– Another technological revolution that had a significant impact was the large-scale introduction of specialized architectures such as the GPUs (Graphics Processing Unit) as co-processors in high-performance computing. Indeed, each computer now has a graphics card that gives it a considerably higher computing speed than the computers of a decade ago; processing power (CPU) has also increased. This increase in performance must be placed in the context of a growing demand for calculations by AR or VR applications. This is, of course, because of the increasing quality of computer-generated images required, as well as interaction with a user, which requires very short cycle times (high calculation frequency, low lag). For example, let us note that in the *Virtual Reality Treatise*, we count on the fingers of one hand the number of times the term GPU is used in the first four books, and this is the same for video processing or the processing of sound signals.

I.3.4. *A revolution in use and users*

The other profound change in the landscape relates to the fact that applications that were initially intended for a few professional fields (often specialized fields, such as design offices and professional experts) were extended to all of society, even entering our homes (e.g. games, services, home automation systems). Over the past 10 years, the augmented reality user has shifted from being an expert working in an office to every Joe and Jane at home or on the move. This also holds for VR-AR equipment, which, up to a decade ago, was only sold by a few distributors known only to insiders. Today, any mainstream vendor selling electronic systems will carry, on their shelves and in catalogues, a complete range of equipment (visioheadsets, sensors) that we can also see sold in large retail stores. It is no longer uncommon for "conventional" stores to offer clients the opportunity to try applications or equipment. This evolution in the use of VR-AR will undoubtedly continue in the years to come.

I.4. The contents of this book

The editorial choices that led to this book resulted mainly from one simple principle: to describe the most notable facts of the last decade and imagine those that may occur over the next decade. Along with the authors of the different chapters, we have therefore prioritized pertinence rather than exhaustivity. Indeed, an exhaustive account of the evolution of such an active field over the last 10 years would require a few thousand pages! Finally, the reader will see, in the bibliographical references listed at the end of each chapter, that some references date back to 10 years or, in some cases, even further back! We have tried to specify original sources in order to honor the history associated with a technology or a scientific contribution, while also showcasing important recent results.

This book is thus organized as follows:

1) Chapter 1: the discussion here is centered on the social impact of virtual reality and augmented reality. What do they bring in and how can they be used in broad fields of applications?

2) Chapter 2: this chapter analyzes the technological revolution in detail, from the viewpoints of both equipment and software, and discusses the impacts of this evolution.

3) Chapter 3: this chapter reviews essential concepts in both technological sciences (computer sciences, electronics) and human sciences (cognitive sciences, ergonomics) and describes the main challenges related to each field.

4) Chapter 4: based on the questions that remain, what are the paths that allow us to offer more satisfactory solutions and allow, among others, for richer user experiences?

5) Chapter 5: in this chapter, we discuss the main evolutions we foresee, while acknowledging the difficulties of this exercise given the strong splits possible in this field. A brief recap of the analysis of evolutions over the past 10 years is sufficient to persuade ourselves of this difficulty.

6) Chapter 6: we will analyze the potential for development related to a mass distribution of VR and AR, while also touching on the potential risks associated with this, with respect to both user safety and unrestrained use of technology.

7) Conclusion: this chapter reviews the different elements discussed in the book and opens up a debate on the concept of virtual reality, as it has been fantasized about in movies or in the literature. We have also attempted to sketch out a few broad paths for the future, inspired, notably, by a debate carried out in the AFRV general assembly[5].

This book approaches a complex and relatively unknown field. The “target audience” is therefore quite wide: students, developers of software solutions, decision-makers, those curious about technology, etc. We thus thought it was important to try and make this book readable across audiences rather than offering a linear reference from the first page to the last. We thought it should be a bit like navigating a website, allowing each reader to click on whatever interests them. Thus, while our structure is based on a certain logic, these chapters may be read more or less independent of each other, depending on the competence and needs of each reader. As a result of this, however, some concepts or notions may be repeated across chapters. This is not to belabor the point, but simply to help each chapter remain “self-sufficient”.

For your assistance, we propose, based on your profile, a nonlinear navigation that allows you to directly arrive at the information you consider to be most important:

– VR or AR student: what can we say except that we recommend that students read it all the way through?

– Software solution developer: we suggest that developers, who may not have the time to read everything, review concepts and recent evolutions (Chapter 1), recall the scientific challenges related to VR-AR and then approach current and future solutions (Chapters 4–6). Here again, we can only recommend that it would be ideal to read the book in its entirety!

– Decision-makers in organizations: apart from this short introduction, it would be important to get an idea of the current and emerging applications (Chapter 2) and then to familiarize yourself with current evolutions in equipment and software (Chapter 3). Having done this, a decision-maker is likely to be very interested in the new developments discussed in Chapter 7.

5 http://www.af-rv.fr

– A curious reader, a technology enthusiast: here again, we would recommend the basics in this introduction, before suggesting you to go through Chapters 2 and 3, which offer a panoramic view of current applications and the technologies used. Chapter 4 will help you understand why implementation is not so simple and why the technologies we see in movies do not yet exist. The conclusion (Chapter 8) will also provide more details on this last point.

– SHS (Social and Human Sciences) experimenters: while reading Chapters 1 and 3 is, of course, recommended so as to understand advances in the field, the human factor is discussed chiefly in Chapter 4 (challenges) and Chapter 5 (current solutions). A brief review of applications (Chapter 2) would not be irrelevant, in light of the earlier chapters. Finally, Chapters 7 and 8 discuss some future prospects that raise important questions for researchers in human sciences.

– A professional in an applicative field: Chapter 2 is obviously essential; Chapter 3 may enlighten the reader as to technologies required for the realization of these applications. Finally, the reader would probably need to go over the solutions in use today to address various problems faced by developers.

I.4.1. *Authors/contributors*

To help integrate this book, we called upon experts from French laboratories, who are very active in the fields of VR-AR, as well as experts from the industrial world, both for offering material and/or software solutions, and for discussing the usage and the integration of these technologies. These experts were brought in with the aim of covering a wide range of competencies inherent to the fields of VR-AR (e.g. computer sciences, signal processing, automation human sciences). We have had long-standing professional relationships with many of them (especially within the AFRV). The list of contributors to each chapter is specified on the first page of the chapter, and a complete and detailed list of all contributors is provided at the end of the book.

I.5. Bibliography

[ART 09] ARTAUD A., *Le théâtre et son double; suivi de, Le théâtre de Seraphin*, Gallimard, France, 2009.