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New Applications

This chapter aims to give an overview of the new families of applications that have emerged or that have undergone massive development in this last decade. The first section (section 1.1) will analyze the manufacturing industry, exploring the development of virtual reality (VR), the emergence of augmented reality (AR) and the question of return on investment. This is mainly illustrated by real industrial examples, shared by the concerned actors themselves. The second section (section 1.2) explores the field of health and analyzes the impact VR and AR have had on training, on preparation for intervention and on uses in the world of surgery. Section 1.3 will examine applications related to city life, architecture and urbanism and will focus especially on developing mobility. Finally, we will end the chapter by looking at recent results in the field of training and in the field of heritage (section 1.4).

1.1. New industrial applications

1.1.1. *Virtual reality in industry*

Until recently, it was impossible to think of virtual reality without imagining using heavy and complex machinery that needed a dedicated team to operate it. These characteristics have certainly put the brakes on this technology being integrated into companies for whom ROI (return on

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investment) is a near-essential criterion for any decision related to making investments.

The broad periods across which companies were involved in AR can be described as follows.

1.1.1.1. *The age of pioneers: researchers*

Until 2005, only a few large industrial groups were interested in virtual reality. Their participation was strongly linked to the group's research activities (fundamental and industrial research) and its interconnections with the higher education and research community. In France, the companies that were involved in research all possessed in-house Research and Development departments that were made up of researchers, doctors, engineers and research engineers working within national and Europe-wide projects, in close collaboration with researchers in large public sector research laboratories (e.g. Inria centers, CNRS units, university laboratories). PSA, RENAULT and AIRBUS are the companies that established this process with the CRV at PSA, RENAULT's Technocentre and EADS IW (renamed the AIRBUS Innovation Group) for Airbus.

1.1.1.2. *The experimenter's age: innovative engineers*

From 2005 to 2010 or so, many large companies learned of the emergence of this technology for virtual 3D prototyping and level 1 immersion. They wished to carry out experiments in order to analyze the potential of virtual reality in different professions (especially research department and organization and methods departments). The approach they adopted was quite different from that of the "pioneers": they did not wish to set up an internal research center, but developed "innovation departments" that were associated with certain platforms for technological resources such as CLARTE at Laval or ENSAM at Chalon-sur-Saône. We can also give the example of DCNS, Plastic Omnium and many more.

1.1.1.3. *The age of shared platforms*

From 2010 to 2014, the widely used model was that of a shared platform available to companies in the region. In effect, as technology matured and its application for various purposes became more robust, many companies requested an institutional environment that allowed sharing of equipment (CAVE, Cadwall) on which the ROI was not realistically high enough for each company to invest in it. This model was initiated at LAVAL in 2000 by CLARTE and its technical platform for companies paved the way for platforms such as CIRV at St Nazaire, Industrilab in Picardie and Holo3 in Strasbourg.

1.1.1.4. *The age of VR headsets and applications distributed on a very large scale: major players on the offensive*

From late 2014, we have witnessed a techno-economic revolution in the field of VR. The field was fundamentally transformed by the appearance of the first Oculus headset, followed by its eponymous successors, as well as other headsets from other companies (each outperforming the other), such as the HTC Vive, all of which were also available at very low costs. Obviously, a headset cannot and may never be able to do the same things a high-end visiocube can. However, the "user-usability-immersion" cost equation for an HMD is such that actors within companies cannot help exploring them and factoring them into their deliberations. At best, they are considered complementary to the visiocube and, in the worst case scenario, they can replace them. It must be noted that the economic model of the HMD has nothing in common with the visiocube. In fact, the HMD is considered, in accounting terms, to be a consumable. Investment related to virtual reality is currently completely related to software and not to equipment, which significantly modifies the decision-making center.

1.1.2. *Augmented reality and industrial applications*

Augmented reality is a technology that has sparked off a lot of fantasies but delivered very little. In effect, many communicators rode on the message "add the virtual onto the real", creating sensational videos that led the viewer to believe that we would completely naturally be able to watch a car that did not exist; visualize the sofa we would buy in our living room; get up close to people who were far away or even people who had died. In brief, that real life would be exactly like a TV series!

However, these promises far outstripped the possibilities that technology can offer today. The consequent backlash resulted in a strong rejection of AR by the public and general users today content themselves with "pseudo-AR" games, like *Pokémon Go*. Unlike with VR, here we cannot trace the stages through which companies appropriated this technology. This is because the needs expressed and the predicted uses resulted in a “pseudo-offering”, which claimed to respond to their demands by using tricks and artifice that did not long stand up to scrutiny. The Gartner Hype curve for 2017 (Figure 1.1) offers an interesting illustration: it quite brutally plots AR in the “trough of disillusionment”.

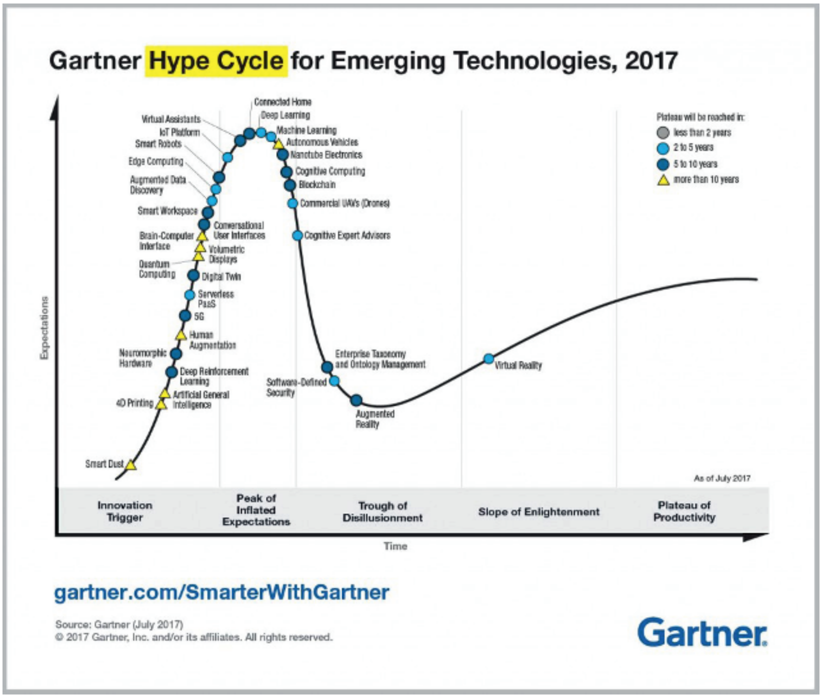

Figure 1.1. *Courbe de Hype 2017. For a color version of this figure, see www.iste.co.uk/arnaldi/virtual.zip*

A careful analysis, however, shows us that *where industrial applications (and these alone) are concerned*, augmented reality has already entered the next phase, the “Slope of Enlightenment”, with market stability expected in the next two-to-five years.

1.1.3. *VR-AR for industrial renewal*

Before we get into a detailed examination of the impact VR-AR technologies have had on the world of business, let us listen to a voice from the industry – Stéphane Klein, Deputy Director of STX (Chantiers de l'Atlantique) and head of the RetD. He offers a succinct summary of the pragmatic steps taken by several leading industrialists and the impact that they have observed:

> "*Innovation is in the DNA of the STX France shipyard in Saint-Nazaire. This is probably why it is the last remaining large maritime construction company and why it is seeing, today, an unprecedented resurgence in activity, with the order-book completely full for the next five years! Keen to offer its clients ever more innovative products, at the cutting edge of technology, STX has constantly upgraded its production system in order to remain on the offensive in a highly competitive global market. The use of virtual reality in association with a new 3D CAD has certainly been among the most significant changes in the STX research department over the last five years. Just a few years ago, Virtual Reality was nothing but a simple "Work Package" in a R&D project – but it has rapidly become an integral and indispensable part of STX study processes and marketing. Today it is mature and systematically used. STX is now looking to use Augmented Reality. This may find applications in the building and operation of ships; in the field of navigation or maintenance of equipment, and also in the construction process. With respect to this last point, STX is currently evaluating the use of augmented reality to assist linesmen/women working with electrical power systems and fluid networks. The initial results from this experimentation are very promising and the gains in productivity and quality have been noted. The industrial use of augmented reality to fit-out ships is quite imminent. What remains is to fortify the solutions studied within this R&D project*".

1.1.3.1. *The fundamentals: research and communication-marketing*

From the early 2000s, leading industrialists have focused on two main subjects, namely:

– virtual reality within the research office (extending 3D CAD) for immersive project review, for verification of assembly–disassembly activities and for interactive design in an immersive experience. VR here is a tool that aids decision-making (Figures 1.2 and 1.3);

– virtual reality within communication-marketing departments, used as a marketing tool to aid sales and adding value to the company's products and services.

Figure 1.2. *The layout for the command post of a ship at DCNS (© CLARTE – NAVAL Group (ex DCNS))*

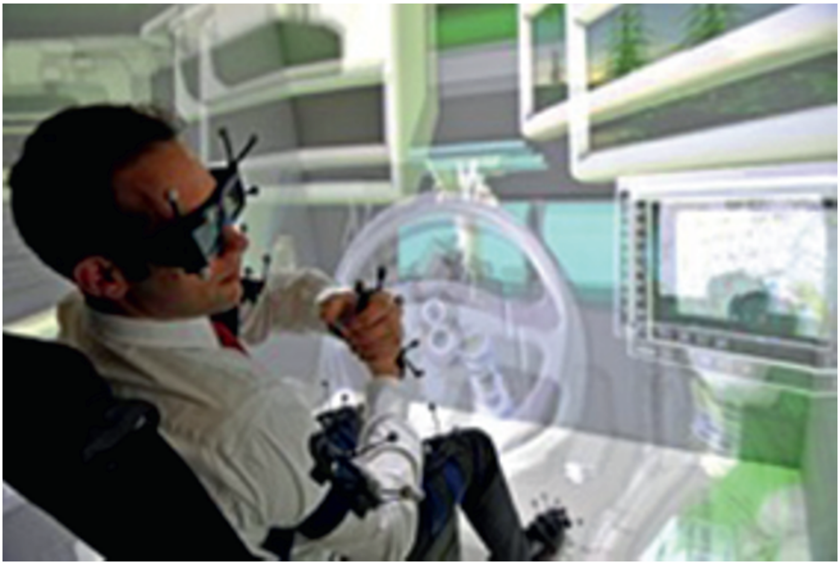

Figure 1.3. *Project review at NEXTER (© Nexter)*

These two areas of development have made it possible for the concerned companies to generate a great deal of enthusiasm within their internal services (see PSA and its CRV) and have allowed France's leading industrial companies to project an image of innovation and to come together and anticipate a new industrial revolution based on collaborative practices (e.g. co-designing with sub-contractors and clients, remote collaboration within entities of the same group). While it is still too early to talk of an industrial revolution, it is clear that VR has contributed to a change in behaviors within research departments and has certainly contributed to the development of new user-centered design approaches, as well as AGILE methods.

Over the years, hardware and software platforms have become professional and, from adopting a rather exploratory approach (the early 2000s), have today become reliable, high-performance and intuitive tools which can be used even by the uninitiated. A few examples of the platforms on the market are: ICIDO from EsiGroup, HIM from Optis, RHEA from Airbus (for Airbus' own requirements), IMPROOV from MiddleVr and TECHVIZ's eponymous platform.

Jean Leynaud (Director of Systems Engineering at NEXTER) gives a detailed account of the impact VR has had on the company's approach to the factories of the future:

> *"Ever since the creation of the GIAT industries in 1971, from design boards to 3D digital models, the weapons manufacturer Nexter Systems has ceaselessly evolved practices and tools to boost performance and innovation. It was in this context that in 2013 Nexter System equipped itself with a virtual reality system (four-sided system working with CLARTE's IMPROOV software).*
>
> "*Virtual reality now makes it possible to involve the end-user more than ever before in the preliminary design phases, as the approach used up to now – reading and understanding CAD views – is not something that everyone can do. This immersion in a 3D environment has sparked off discussions that are much more pragmatic and directly related to operational use. Thanks to VR, the end-user can enter into the environment much more easily and feel as if they are already in their vehicle. It is thus easier for them to describe what they feel and what they need. This collaborative design is a significant advance for Nexter and their clients. This*

new manner of direct design also makes it possible to concentrate on the architecture and to go further with the innovation of future products in the NS range. For about three years now, VR has been an important part of the Nexter development process. Each project uses 3D immersion for reviewing concepts. This makes it possible for all actors, especially those who cannot access CAD routinely, to share in the global vision of the product at key points in the development and to better understand the different choices in architecture. VR has become an indispensable resource in developing new products in order to choose an architecture and to "de-risk" the launch of a physical mock-up (without replacing it). For example, reworking a physical model will require several months for the retrofit and a large financial investment, while modifications carried out on the virtual model will require only as much time as it takes to manipulate it on the computer. This allows a great deal of flexibility and speed of iteration for the model, which is significant especially in an industrial context where development time is restricted."

Another representative example is that of La Redoute. After their research department had worked on the layout of their new warehouse and the ergonomics of different production posts, the company used virtual reality as a social mediation tool by putting into place a large-scale internal communication operation. A presentation of the virtual model for this future warehouse was presented to all the collaborators via HMDs within the company over the period of a week. The impact was tremendous, as Marc Grosclaude recounts in an article published in La Voix du Nord: *"In a year and a half, La Martinoire will have been completely transformed: farewell to the [old] warehouse, which was considered "ultramodern" when its foundation stone was laid in 1968. To comprehend the scope of the transformation, the employees of La Redoute were able to explore the order-processing site in 3D. We were given the same virtual tour...."*

Thanks to VR, we can talk about industrial and social renewal in very concrete terms. Let us note, however, that SMEs, and even larger businesses, were quite nervous about using VR until quite recently. This was because of the large cost of acquiring and then using the equipment, and also because the ROI is hard to calculate. If some companies did manage to understand, quite early on, the benefits of using this technology (direct ROI vs. the less-quantifiable indirect ROI), it was because clients with large orders led to their entering the world of collaborative projects.

1.1.3.2. *Ergonomics and training: perfect illustrations for value added by VR*

1.1.3.2.1. Ergonomics – objective: reducing musculoskeletal disorders

While the decade from 2000 to 2010 saw large-scale development in applications in the vertical sectors of the industry (terrestrial, petrochemical, naval and aeronautical vehicles), recent years have seen many transversal uses emerge, such as ergonomics and collaborative work on virtual prototyping and training. The economic stakes for all three fields are huge and the ROI is relatively easy to calculate.

As concerns ergonomics, two different areas are involved: ergonomics of usage (pilot's seat or command and control posts) that make it possible to concretely improve the usability and intuitiveness of various equipment, and postural ergonomics (ergo-design of production posts and lines), which makes it possible to drastically reduce musculoskeletal problems by carrying out a downstream study of workposts (Figure 1.4).

Figure 1.4. *Ergonomic study on a Lactalis production post (© CLARTE). For a color version of this figure, see www.iste.co.uk/arnaldi/virtual.zip*

One of the most interesting examples of this approach is that of the company INERGY (Plastic Omnium group), which was one of the first companies to experiment with an Ergo-designing application for production posts, developed by CLARTE. Very quickly after a few tests were carried out on some new production lines (Figure 1.5), the company decided to systematize this process: since 2011, any new production post (in any INERGY site around the world) has been designed via an ergonomics study carried out using VR and the RULA (Rapid Upper Limb Assessment) method. The impact this application had was so significant that Plastic Omnium decided to create its own virtual reality center within its technical center (Compiègne) and to use it for its businesses. INERGY estimates that it has managed to shave off about 20% of the time spent on its design-creation phase and has seen its "reworking due to design error" rates plummet for new posts, as the downstream participation of workers in the company has been particularly beneficial.

Figure 1.5. *Ergonomic study of an Inergy production post (© AFERGO)*

The typology of companies using this approach is interesting. There are, of course, large groups, as well as a good number of their sub-contractors, generally placed between medium- and large-scale businesses, as well as several medium-scale businesses that today use "virtual design" in their sales arguments.

1.1.3.2.2. Training: a revolution in engineering pedagogy

Training is certainly one of the sectors where VR has had the greatest impact (Figure 1.6). The four main reasons for this are:

1) the simulation of work situations using 1:1 scale immersion and multisensory interactions that make it possible to put in place a new pedagogy for engineering that is perfectly in line with training objectives;

2) total "de-risking": the learner can be placed in all kinds of work situations, including those that are dangerous, in order to teach them the actions and procedures to adopt and to help them acquire the correct reflexes in case of danger;

3) savings on consumables (e.g. training in industrial painting without spoiling any raw material) and heavy equipment (e.g. production equipment need not be set aside for training, resulting in improved productivity overall);

4) the attraction of using 3D images and immersion can help offset the more boring aspects of traditional training.

Figure 1.6. *Training to land and take-off on a helicopter carrier (in choppy conditions) (© CLARTE - NAVAL Group (ex DCNS))*

Let us note that beyond the innovative training process, many companies use VR applications to sensitize future employees (e.g. youngsters, job applicants) to the work and the available posts. Virtual reality here becomes an extremely efficient communication tool used by HR services to add value, to help build understanding and to recruit. The associated business model is still simple, as the ROI is calculated using the following equation: (savings on raw material + savings due to production equipment not being blocked for training) – (cost of acquiring and using the VR training platform).

The recent emergence of low-cost and very high-performance HMDs makes this a highly positive equation, resulting in the current boom in teaching and training applications.

1.1.4. *And what about augmented reality?*

While AR is simpler for the general public to understand as they have used smartphone and tablet applications, we have seen that they lost interest in it. However, AR continues to progress in the professional, especially industrial, world.

There has also been a remarkable evolution of equipment. Microsoft's HoloLens glasses mark a significant progress in this field.

Even in 2017, it is still difficult to talk of industrial renewal being ushered in by AR, as the applications that are most mature and used concretely within companies are focused on communication, marketing and improving sales.

Having said that, there are many ongoing research projects, and it is quite probable that mature applications will be available in the coming years, initially using tablets and other intermediate screens and later using semi-transparent glasses. Moreover, some applications have already attained a degree of maturity that will allow them to participate in the industrial renewal we are currently living through.

Let us take the example of MIRA (Figure 1.7) developed by AGI (Airbus Group Innovation) *"This solution was first used so the aviator could verify the integrity of the correct placement of thousands of parts installed in airplanes, such as the fixed supports that hold up electric cabling, hydraulic pipes or air-conditioning pipes"* (an Airbus source).

Figure 1.7. *The MIRA application from the Airbus Innovation Group (© Airbus Group). For a color version of this figure, see www.iste.co.uk/arnaldi/virtual.zip*

Let us also give the example of ARPI (Figure 1.8), an experimental device to control the assembly of equipment in a "panel factory" within STX (the ship-building yard at St Nazaire), which made it possible to save a significant amount of time.

Unlike virtual reality, which largely concerns research departments and Organization and Methods departments, augmented reality is used in the field, even within production units and in the construction of the industrial world. The equipment used (tablets, PCs, AR glasses) is thus quite strenuously tested, and it is imperative that it be robust, reliable and intuitive when implemented. If this is the case (a real challenge!), the value added by these AR applications is very large and is much easier to measure by ROI and productivity specialists than for VR.

Offering assistance to an operator in a control room, helping a metallurgical worker in guiding and positioning, offering local or remote technical assistance to a technical maintenance officer – all of these uses will lead to measurable gains in the productivity of several dozen percentage points.

Figure 1.8. *The ARPI application to control panels (25 m*25 m) STX (© CLARTE - STX)*

1.2. Computer-assisted surgery

Software for the simulation, planning and training to carry out operations: navigational help; AR devices; remote interventions; robotics... computer-assisted surgery is a growing field and one that has already entered several operation theaters. This section gives a description of the current situation in the field and the main challenges and prospective paths in this revolutionary sector, by focusing on the contributions of VR-AR to the past decade and to the coming decade.

1.2.1. *Introduction*

Ever since the first radiograph and the first use of X-rays in 1895, medical imaging has only improved and diversified. It saw significant progress from the 1970s onwards with the development of the CT scan, and from the emergence of nuclear medicine and magnetic resonance imaging, which appeared in the early 1980s. This major evolution in the medical field was, however, only possible due to the joint development of computer sciences and digital image processing methods, which made it possible to interpret and process increasingly larger and more complex images with greater precision and efficiency.

Today, we see a new revolution taking place in the medical field, thanks to techniques such as digital simulation, 3D modeling, biomechanical characterization, and virtual and augmented reality. These developments have also set up links with medical imaging and robotics by widening their scope of application. There are already many uses for VR in medicine, if only to interactively visualize 3D patient data reconstructed from a CT or MRI scanner. It is, however, possible to go much further, combining results achieved in different scientific fields.

In this section, we will examine the field of computer-assisted surgery, which is at the heart of this revolution but also poses several challenges. The three main challenges are: 1) the use of VR to train surgeons in an appropriate training course, where there is no risk to a patient; 2) upstream planning of complex interventions, in order to reduce surgical time and risks; and 3) the use of AR in the operation theater in order to bring together, *in situ*, the essential information needed for the intervention to be carried out smoothly. In different applications, several physiological, biomechanical and geometric parameters are brought into an equation and calculated: for example, deformation on the liver, electrophysiological activity in the heart or even physical interactions between surgical instruments and an organ (see Figure 1.9).

There are strong associations between these different objectives that make it possible to share scientific results. In most cases, therapeutic targets are soft tissue[1]. Organs such as the liver, heart, brain and blood vessels represent a large part of anatomical structures on which surgical interventions are carried out. Modeling these structures, not only from an anatomical point of view but also from a biomechanical point of view, is an initial challenge that is common to all three objectives. The simulations used for learning and for assistance during surgical operations also share another common point,

1 Soft tissue is any tissue in the body other than bone, such as muscle, fat, fibrous tissues, blood vessels or any other supporting tissue.

related to computing time. In order to allow interactions or instant display of information, these applications require the result in real time. This is difficult given the complexity of the biomechanical models discussed earlier, which require several parameters (and thus computations) to be taken into account. Finally, pre-operation planning and intraoperative[2] assistance require a high level of precision in predicting the results supplied by the calculations. This precision is achieved by using increasingly powerful digital calculation methods, and also by specific modeling, adapted to the patient, and not the generic modeling that is usually used in learning software. We use the term "personalized medicine".

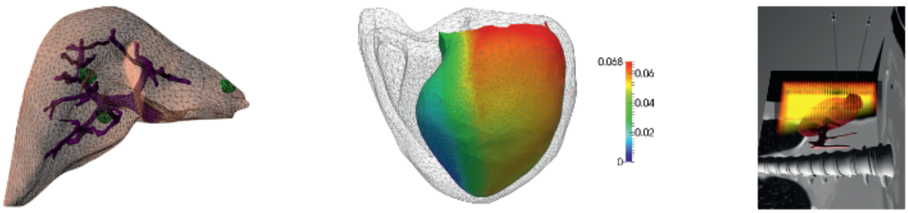

Figure 1.9. *Left: digital model of the liver and its vascular network, created using a patient's CT scan and adapted to real-time simulations. Center: simulation of electrophysiological activity of the heart, parametrized using patient data. Right: simulation of the cryoablation of a renal tumor and its calculation grid (in yellow and red). For a color version of this figure, see www.iste.co.uk/arnaldi/virtual.zip*

In this chapter, we will first discuss the AR techniques that can potentially visually enrich information through a fusion of intraoperative images and preoperative data (e.g. images, virtual 3D models), which help guide the surgeon during the operation. However, in order to progressively introduce the different concepts brought into play by this domain, we will begin with results from the use of VR in the learning context (section 1.2.2) and in the planning of operations (section 1.2.3).

1.2.2. *Virtual reality and simulation for learning*

In this section, we will briefly present a few examples of VR being used in the context of learning in the field of surgery. Rather than providing an

2 Anything that is done during the surgical intervention is called an intraoperative procedure.

extensive report on existing projects and products in the field, we wish to introduce a set of concepts that will be helpful in understanding the rest of section 1.2. Generally speaking, interactive digital simulations developed in this context are mainly meant for minimally invasive surgeries[3]. These new approaches offer multiple advantages to the patient such as lowering the risk of infection and hemorrhage as well as shortening the duration of hospitalization and rehabilitation. However, given the reduced field for the surgery (because it is viewed through an endoscopic camera) as well as the absence of any tactile information during these interventions, specialized training is absolutely necessary. Fortunately, this surgical technique presents characteristics that made it easy to develop VR tools and simulations. As there is no direct manipulation of the organs, nor a direct visualization of the surgical site (see Figure 1.10), it is possible to develop devices that faithfully reproduce what the surgeon perceives in reality.

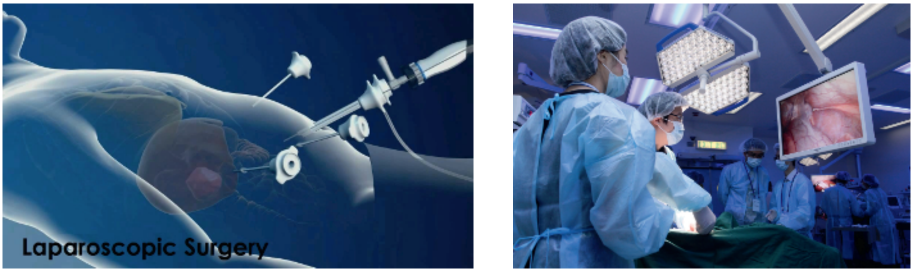

Figure 1.10. *General principle of laparoscopic surgery: miniaturized instruments and a camera are introduced into the abdomen through small incisions. The surgeon then operates using a monitor that displays what the camera captures. For a color version of this figure, see www.iste.co.uk/arnaldi/virtual.zip*

These concepts also cover the fields of micro-surgery or vascular surgery. In the first case, the surgical site is most often visualized through a stereoscopic microscope and the instruments are sometimes similar to those used in laparoscopic surgery[4], but in a miniaturized form (see Figure 1.11).

3 Minimally invasive surgery consists of operating using miniaturized instruments, inserted through small incisions and manipulated with the help of imaging techniques.

4 Laparoscopic surgery is an example of minimally invasive surgery, used for abdominal surgery. The imaging device is a miniaturized camera (the laparoscope), which allows a visualization of the abdominal cavity.

As concerns vascular surgery, also called interventional radiology, the visualization of the anatomy is carried out through a system of X-ray images and the therapeutic action is carried out via flexible instruments (catheters and guides), navigating up to the concerned region through the arterial or venous system (see Figure 1.12). This technique allows vascular surgeons to carry out interventions on arteries (e.g. aorta, carotid, coronary) or to treat pathologies that can be directly accessed through the vascular network (e.g. cardiac valves, local chemotherapy for hepatic tumors).

Figure 1.11. *Micro-surgery is also a field of application where simulations can be developed for learning. Here, we have the simulation of a cataract operation and its force-feedback system (© HelpMeSee)*

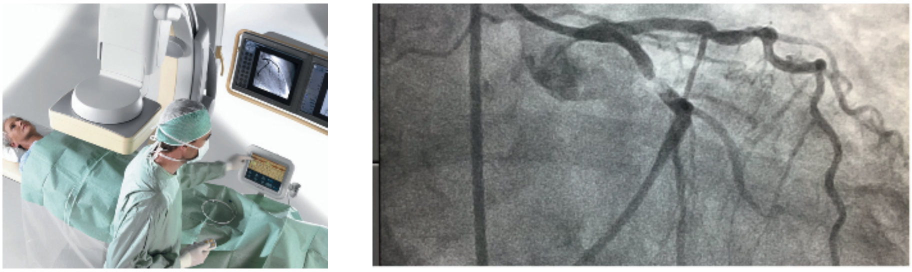

Figure 1.12. *Vascular surgery uses microsurgery which navigates the vascular network, until it reaches the pathology. The visualization of the intervention is carried out through a real-time X-ray imaging system called fluoroscopy*

Regardless of the field of application, a preliminary step consists of generating a 3D anatomical model. The interventions are most often specific to an organ and thus this model is limited to a few anatomical structures (e.g. liver, heart, eye), but may, sometimes, be wider, such as a model of the vascular system. This model may be constructed directly, using volumetric medical imaging (CT, MRI or other methods) or using 3D modeling tools. Current approaches tend to combine both these methods, first creating a model based on real data and then editing this to match the simulation constraints or to add anatomical or pathological variations.

Creating a precise 3D representation of anatomy, even only locally, still poses a challenge today. There are several reasons for this. First of all, surgery is essentially based on visual perception and surgeons are trained to interpret visual inconsistencies as indicators of possible problems or a pathology. Thus, in order to make the virtual representations as realistic as possible, each geometric detail or texture must be integrated and cannot be deleted to make the representation lighter, as is done in other fields (e.g. industrial design, architecture). Furthermore, this anatomical model, unlike other VR applications, cannot remain a simple geometric representation. It will be used as the basis for a physical model (e.g. mechanical, electrical), which also brings in its own set of constraints. We will return to this further down. Figure 1.13 illustrates one of these representations of anatomy, in this context being used for training in local anesthesia.

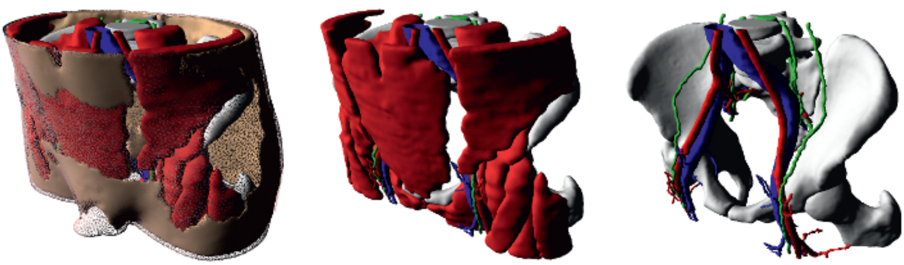

Figure 1.13. *Modeling anatomy, as well as creating geometric models adapted to different calculations, is the first key step in simulation for learning. It can provide different levels of detail. For a color version of this figure, see www.iste.co.uk/arnaldi/virtual.zip*

This technique consists of injecting the anesthetic directly into the nerves, thereby avoiding the need for general anesthesia. This model therefore needs to include different levels of representation, going from the skin and muscles up to nerves and arteries. A CT scan and an MRI were the basic images used to obtain these multiple levels. After processing the image and then carrying out 3D reconstruction, the different meshes were reworked so as to guarantee certain properties.

The characteristics that we wish to obtain in these meshes are related to the geometry and topology of the mesh. For example, it is important that the meshes be "smooth", as most anatomical structures have this property. It is also important to guarantee that the surfaces are closed when they define volumes. This will make it possible to manage contact between virtual objects (if there is a hole in the mesh, we can go through the object without detecting any collision) and we can also create volumetric meshes that can be used as supports in computing strains (see Figure 1.14).

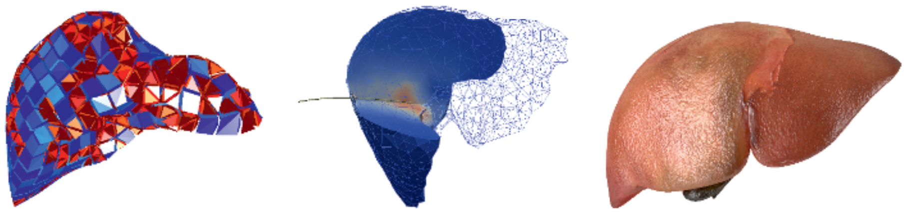

Figure 1.14. *Left: finite element mesh of the liver, made up of tetrahedra and hexahedra. Center: simulation of the interaction between a radiofrequency electrode and the liver, which requires computing strains and calculating the contacts between the instrument and the organ. Right: visual model of the liver, with realistic rendering using textures and different lighting models (shaders). For a color version of this figure, see www.iste.co.uk/arnaldi/virtual.zip*

Apart from a few specialized surgical fields, such as orthopedics, the anatomical structures that we are examining are considered deformable. To accurately integrate them in the context of learning, planning or surgical assistance involves modeling their biomechanical behavior. This modeling is most often based on the laws of physics, but with different degrees of approximation with respect to real behavior. Thanks to the development of new digital approaches, it is now possible to use behavioral models that are quite evolved while remaining compatible with real-time computation [COT 99, COM 08]. Many researchers prefer using the finite element method (FEM) to achieve this, given its numerical precision. This method requires the creation of a volumetric mesh (see Figure 1.14), composed of simple geometric elements on which the computations are carried out. As Figure 1.15 illustrates, the precision and rapidity of the computations are influenced by the type and number of these elements.

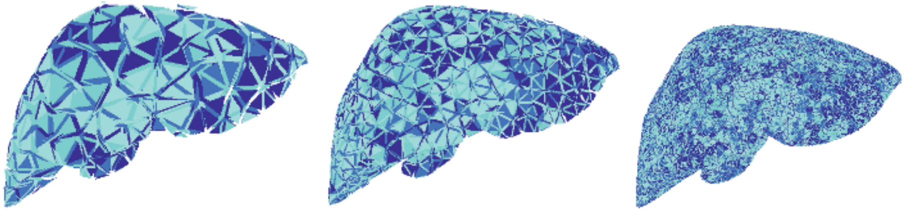

Figure 1.15. *Left: finite element mesh of the liver, composed of 1500 tetrahedra, with a computation time of 8 ms (i.e. 125 images/second). Center: finite element mesh of the liver composed of 4700 tetrahedra, with a computation time of 25 ms (i.e. 40 images/second). Right: finite element mesh of the liver composed of 21,600 tetrahedra, with a computation time of 140 ms (i.e. 7 images/second)*

Regardless of the chosen approach, what sets the field of surgery apart from all the other fields where VR is used is the deformable nature of the structures. This also explains why the term *simulation* is often substituted for "VR", as the real-time digital simulation of strains and the interactions with virtual instruments remain the predominant source of complexity. These interactions may be of widely varying natures depending on the organ, the pathology and the surgical technique. In the case of a "traditional" surgery, the instruments are mostly rigid and used to cut, cauterize and suture the organ. In other cases, such as vascular surgery, the instruments are flexible and will interact with the blood vessels, which are more rigid than the instrument. This results in different modeling techniques where the computation time will essentially be given to compute the strain on the instrument and not on the organ (see Figure 1.16).

1.2.3. *Augmented reality and intervention planning*

In some cases, surgical planning is absolutely essential to the success of the surgery. In the case of a hepatectomy[5], for example, this planning will

5 Hepatectomy is a surgical process whereby a part of the liver is removed as a treatment for hepatic tumors.

make it possible to maximize the volume of the liver remaining after the surgery, in order to increase the patient's chances of survival. In other cases, this planning will lead to a decrease in the duration of the intervention, thereby also reducing the period of hospitalization. In general, the patient first undergoes medical imaging exams (e.g. scan, MRI, X-ray) in order to obtain images of the anatomical region to be operated on. Today, these images are the basic information used to plan the intervention.

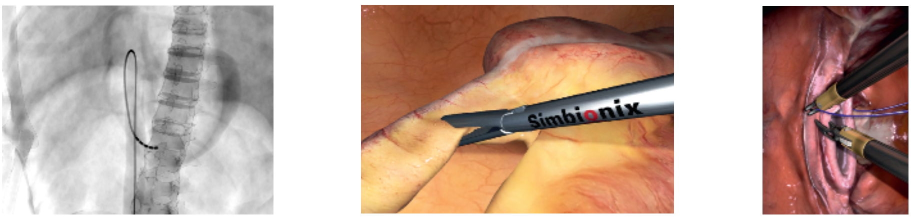

Figure 1.16. *Examples of interactions between the virtual models of organs and the instruments. Left: simulation of the navigation of a catheter in vascular surgery. Center: simulation of an incision in laparoscopic surgery. Right: simulation of a suture in laparoscopic surgery. The interactions are complex in all three cases and in the first and the last examples, the interactions involve other deformable structures apart from the organ itself (© Mentice (left), 3D systems (LAP Mentor) (right))*

They are first studied by radiologists in order to establish a diagnosis and are then examined by a surgeon. However, in certain cases, it is difficult to judge the best strategy to use based solely on these images, or at least based on only viewing them in native form (see Figure 1.17). Hence, these images are most often processed using different software, allowing for an optimal visualization and better manipulation in 3D.

The most widely used method of visualizing these 3D medical images consists of using volumetric rendering techniques. This technique is widely available on workstations in radiology departments and is sufficient to yield a good 3D visualization of anatomical and pathological structures. However, some computations and manipulations are not possible using this technique. In many cases, we need to calculate the volume of tumors; or, using the example of the planning required for a hepatectomy, we need to calculate the liver volume remaining after the surgery as this is a critical factor in determining the success of the intervention. This is done by recognizing and marking out each anatomical and pathological structure in the medical image.

The 3D models obtained (e.g. arteries, veins, nerves, tumors) may then be visualized and manipulated individually, offering a solution that is better adapted to surgical use and planning. Today, a large number of software allow the surgeon to carry out these manipulations: Myrian (Intrasense, Montpellier France), MeVisLab (MeVis Medical Solution, Germany), ScoutLiver (Pathfinder Therapeutics, USA) or even VP Planning (Visible Patient, France). The virtual patient obtained using the software can then be used to facilitate or optimize the diagnosis or planning of the surgery.

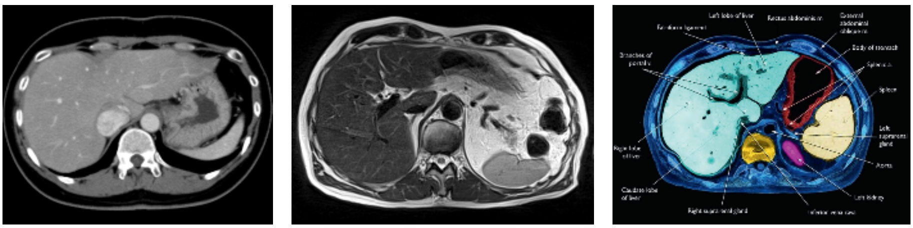

Figure 1.17. *Examples of medical images used for diagnosis or planning. Left: image taken from a CT scan. Center: image from an MRI scan. Right: labeled image indicating the different anatomical structures visible in the image*

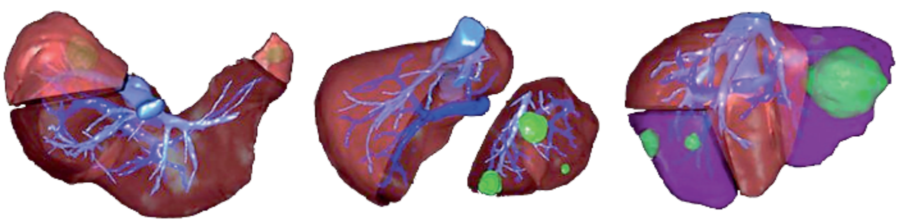

Figure 1.18. *Planning of a hepatic surgery in virtual reality, using 3D reconstructions of the patient's anatomy. Here, the regions of the liver containing the tumor are clearly marked in order to estimate the liver volume, which will remain an essential criterion for post-operation survival (© IRCAD & Visible Patient). For a color version of this figure, see www.iste.co.uk/arnaldi/virtual.zip*

By visualizing and manipulating this virtual copy from all angles, the surgeon can refine the diagnosis and, above all, plan the surgical gestures to perform with a high degree of precision. At this point, we can define three levels of assistance that VR can offer surgeons. The first consists of providing software that makes it possible to simulate the operation in 3D, but without seeking to have a real-time interaction with or manipulation of the realistic virtual model. This is primarily a desktop tool that enables certain calculations or geometric and topological operations to be carried out on the virtual model(s). The second scenario goes further along the path of "virtualizing" the operation, as it can provide an opportunity to rehearse the key part of the operation, after having planned it, in real conditions. Here, we combine the learning principle described above with that of planning the surgery. This service is offered by different companies that specialize in simulation for learning purposes (e.g. Mentice, Simbionix or CAE Healthcare) and is also used by research teams [CHE 13, REI 06]. Finally, the last level of assistance consists of transposing the result of this planning into the operation theater, using complex algorithms that allow the *preoperative* planning to be adapted to the *intraoperative* context.

In all of the above scenarios, scientists focused mainly on improving the quality of simulation and planning, the objective being to make these processes capable of using more data. With the development of new modalities of imaging and sensor systems, it is possible to measure an ever-increasing quantity of information. This diversity allows the surgeon to take more informed decisions and carry out planning that is better adapted to the patient. However, in order to do this, it is essential that these different sources of information and different kinds of data be combined, so that the user can make better sense of them.

For example, by combining the mechanical characteristics of the patient's heart (such as its elasticity) with its electrical activity, the doctor is able to determine the strategy that is best adapted to that patient [TAL 13]. The concept of personalized medicine is thus strongly linked to intervention planning (see Figure 1.19). This evolution takes place through the fusion of data from diverse sources (e.g. MRI, scan, ultrasound), through the development of new sensor systems, and through the creation of more powerful algorithms. For example, a personalized model of the heart, which combined biomechanical and electrophysiological aspects, was developed within the European project, euHeart [TAL 16]. Similarly, in neurosurgery, the combination of preoperative images, 3D modeling and simulation techniques made it possible to offer enhanced tools for the planning of an intervention to carry out deep brain stimulation [BIL 14, BIL 11]. In this surgical procedure, an electrode must be inserted into a zone measuring $8 \times 2 \times 2$ mm^3, located in the center of the brain. Without precise planning, and if the movements of the brain during the operation are not taken into account, locating this structure becomes very complicated and highly time-consuming, not to mention the impact this may have on the patient.

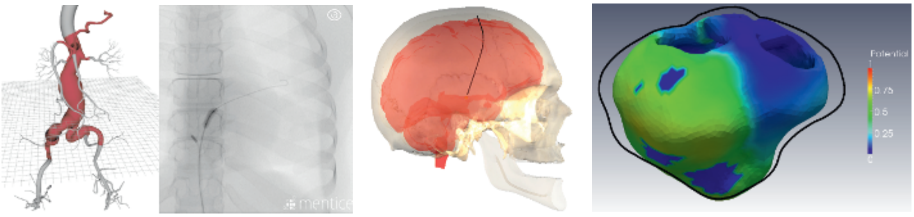

Figure 1.19. *Examples of the simulations associated with surgical planning. Left: patient-specific simulation of a vascular surgery. Center: simulating the insertion of an electrode in a deformable model of the brain to plan a deep brain stimulation. Right: combining a biomechanical model and an electrophysiological model of the heart, configured using data recorded from a patient. For a color version of this figure, see www.iste.co.uk/arnaldi/virtual.zip*

Finally, the specifications and constraints associated with the use of VR in planning surgeries are very different from those defined earlier for learning. Interactivity and real-time processing are no longer mandatory, unless we wish to combine the planning and interactive simulation. However, the precision of the digital simulation remains an essential factor. While a generic and plausible deformable model is sufficient when learning, when the tool is being used for planning, we must go much further with the modeling. As the constraint related to computing time is less demanding, it is possible to use finer meshes for finite element calculation, thereby making it possible to gain in precision. We must also ensure that the physical model that describes the phenomenon is able to correctly represent this phenomenon. We expect the simulation to be predictive. A large body of experimental work is first required to model the phenomenon (e.g. strain, physiology, diffusion of heat) correctly and then to use new data to confirm whether the simulation's predictions are as close to reality as possible [CHA 15]. Obtaining this data is a delicate task and requires the definition of complex experimental protocols and access to specialized equipment. This work, however, remains essential in order to provide surgeons with a tool they can rely on.

The final step, after planning, is the actual surgical intervention. Here, VR gives way to AR in order to combine the information collected during the operation with models developed in the planning stage. Many challenges must be resolved before arriving at this stage in order to guarantee precision, interactivity and robustness in an environment that is less controlled than that of a research laboratory.

1.2.4. *Augmented reality in surgery*

The striking developments in medical imaging over the past 20 years have, today, resulted in the emergence of hybrid surgeries. These are surgeries where imaging systems, usually restricted only to diagnosis, are also used in the operation theater. Surgeons are thus faced with the task of mentally integrating this information (2D or 3D images) into the surgical field. In addition, apart from the rare cases, where the surgeon has access to a hybrid operation theater (see Figure 1.20), interventional imaging resources remain limited (in availability and technical capabilities). The images acquired in an operation theater are thus less precise and less usable than those taken before the intervention using a CT or MRI scan, for example. However, most often, the only device accessible in operation theaters remains the surgeon's laparoscopic camera which only allows them to view the surface of the organs.

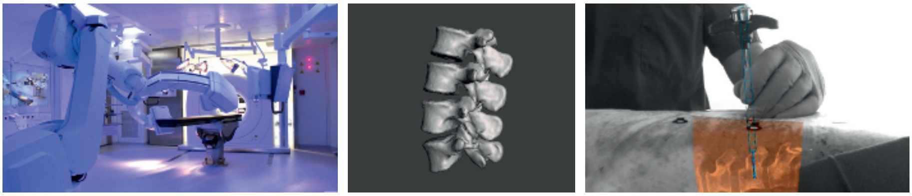

Figure 1.20. *Augmented reality in the operation theater. Left: hybrid operation theatre integrating different imaging systems that allow the visualization of the patient's internal anatomy during an operation. Center: 3D reconstruction of the vertebra before a vertebral column surgery. Right: view in AR facilitating the positioning of a vertebral screw (© Philips)*

To help the surgeon overcome these difficulties, AR aims to display the 3D model of the patient's anatomy by overlaying the real video-operative images. The surgeon's real view is enriched and informed by the virtual information.

The patient thus becomes virtually transparent to the surgeon's view, allowing them to visualize structures within the organs (e.g. vessels, tumors), which they would otherwise be able to perceive only through the sense of touch. An example of AR application in rigid structures is a surgery of the vertebral column. This surgery is a difficult and high-risk procedure as vital parts of the anatomy of the vertebral column and the neurovascular structures are not visible to the surgeon. In order to overcome this, a hospital in Stockholm, in collaboration with Philips, developed an AR technique that combined an external high-resolution view of the patient's surface with a 3D internal view of their anatomy (see Figure 1.20). While, in this case, the complexity of the system is limited, as there are no deformable structures to take into account, this real-time 3D view enables the surgeon to improve the planning of the procedure, the precision of placement of the implant and the treatment time [ELM 16].

Although commercial AR applications for medicine are still very limited, much research is being carried out in this field [FIS 07, HAO 13, LEI 14]. However, they often hypothesize advanced imaging techniques or dedicated markers, in order to facilitate tracking the movement of an organ or instruments. In addition, in order to simplify the algorithmic problems and computation times, it is also often assumed that the anatomy is not deformed (or this deformation is negligible) between the preoperative acquisition and the time of the surgery. Though this hypothesis is acceptable for certain anatomical structures, such as bones, this is not the case for the majority of organs, which are made up of soft tissue. One of the first studies on the use of AR in laparoscopy was proposed by Fuchs *et al.* [FUC 98]. This project focused on the extraction of information on depth from the laparoscopic images, in order to improve AR visualization during the surgery. In the context of visualization again, Suthau *et al.* [SUT 02] described the general principles that still prevail in applications for augmented surgery. In 2004, Wesarg *et al.* [WES 04] described an AR system for minimally invasive interventions in which only rigid transformations, between pre- and intra-operative images are considered. In the same year, Marescaux *et al.* [MAR 04] reported the first AR-assisted laparoscopic adrenalectomy, based on a manual alignment of the virtual model and the surgery images (alignment carried out from a control room located outside the operation theater). Similar results have been obtained from other surgical fields, such as vascular surgery [ANX 13]. However, just as with the earlier results, deformations in anatomy have been ignored or assumed to be negligible. The earliest AR approaches on deformable organs were carried out using markers or navigation systems placed at proximity to the operating field [TEB 09]. These methods have demonstrated that automatic AR systems in surgery are feasible, but generally impose some restrictions on the equipment in the operating room or require manual interaction. (see Figure 1.21).

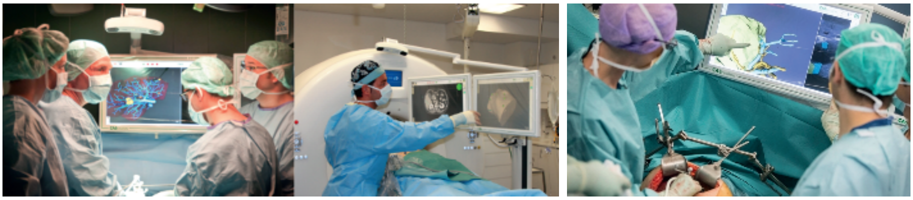

Figure 1.21. *Example for the use of a navigation system in surgery. We can see the cameras used to track the movement of the instruments and the markers situated on the instruments and/or on the organ to facilitate the repositioning of the virtual view, depending on the surgical view. This approach does not manage deformations in the organ nor the visual overlapping of the virtual model and the real image (© CAScination)*

Two terms co-exist in the field of surgical assistance when we examine the fusion of pre- and intra-operative data: if the image is in 2D, whether this is acquisition through X-rays or an image from a laparoscopic camera, the positioning of the virtual object on the real object is often called *pose estimation*. The pose estimation aims to determine the characteristics of the imaging equipment (typically a camera), so as to define a virtual camera having the same characteristics, thereby guaranteeing the optimal overlay of real and virtual images. This alignment is called *calibration* when the interventional image is volumetric, or sometimes just through a misuse of language. This process consists of finding similarities between images, or between an image and a model, so as to define a set of common points between the data. When the calibration is rigid, only a few points are needed. When the calibration is deformable, a much larger number of points must be determined, which is usually more complex to compute. In this case, the deformable model plays a determinant role because, if it describes the physical properties of the organ well, it offers the possibility of precisely extrapolating movement beyond these points, even though they are small in number. As the stereoscopic camera in surgery becomes more widely accessible, Haouchine *et al.* [HAO 15] use them via a method that uses a pre-calibrated stereo-endoscope. Points of interest are marked on the surface of the liver on the pair of stereo images, and these points are then temporally tracked using an optical flux method. This makes it possible to define a characteristic set of points based on their “signature” in the image, which can be identified in each pair of stereoscopic images. By matching the closest neighbor between the points of interest, we can then reconstruct a 3D point cloud by triangulation, which is then smoothed out using the Moving Least Squares method, so as to obtain the least noisy reconstruction of the organ surface (see Figure 1.22).

Figure 1.22. *3D reconstruction of the surface of the liver, using a stereo-endoscopic image. Left: left image with extraction of points of interest (in green). Center: partial 3D reconstruction of the liver based on these points of interest. Right: right image with extraction of points of interest (in green). For a color version of this figure, see www.iste.co.uk/arnaldi/virtual.zip*

It is, of course, possible to use other methods to identify the characteristic points in intraoperative data, with each approach often being linked to a specific imaging modality. Thus, when the interventional images are X-ray images, we can use very small radio-opaque markers so as to obtain visible points both in the pre-operative image and in the intra-operative image. These markers are percutaneously inserted (using a needle) into the organ before the pre-operative scan. By matching the markers visible at the time of the intervention with those extracted from the preoperative image, it is possible to define a transformation between the two sets of points. When we examine a deformable anatomical region, such as the brain or the liver, this transformation is complex but may be assumed to be locally rigid, in a zone around a tumor, for example (see Figure 1.23). The CyberKnife® system makes use of this hypothesis to locate the position of a tumor in 3D using the position of a set of markers placed on the periphery. These markers are captured by two X-ray cameras installed in the wall of the operating room and the 3D position of the tumor is then used to guide a robotic arm onto which a compact linear accelerator is installed. Thanks to the estimate of the position of the tumor, this accelerator focuses a beam of gamma rays onto the tumor, with great precision, minimizing the impact on the healthy tissue around it [KIL 10].

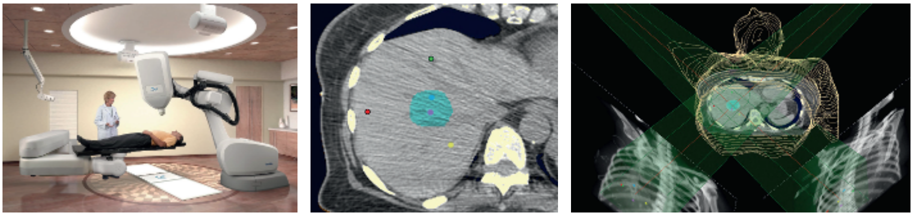

Figure 1.23. *Use of radio-opaque markers to match the pre-operative and intra-operative data. Left: CyberKnife system for radiotherapy. Center: pre-operative image showing the tumor and the markers placed on the periphery. Right: double X-ray beam to identify the 3D position of the markers during the intervention (© Accuray Incorporated)*

In the majority of situations, however, it is difficult to place markers or extract points of interest in an image in immediate proximity to the tumor. As the organs are deformable, in these cases, it is essential that the *calibration* method takes into account the nature of these deformations. Biomechanical models have proven the most appropriate choice for this, as they make it possible to define the organ's elastic properties and, using this, deduce the movements of structures deep within [SUW 11]. The calibration is carried out either by resolving mechanical equations, considering the tracked points as external constraints [SUW 11], or by making use of the concept of active model. The latter is done by minimizing an energy that takes into account the internal behavior of the model and external constraints that measure the degree of the match between the model and the image indices [SHE 11]. A method using a heterogeneous biomechanical model was proposed in Plantefeve *et al.* [PLA 15], the aim of which was to enhance the quality of the AR while also guaranteeing real-time performances. The virtual liver is described by a model composed of parenchyma and vascular network, so as to best represent the anatomical reality while modeling the heterogeneity and anisotropy of the deformations. This model is computed using the finite elements method and can take into account nonlinear, real-time elastic deformations. Peterlik *et al.* [PET 12] demonstrated the precision and high computing speed of this model. This volumetric model is therefore capable of propagating within the volume the 3D deformations observed on the surface using a stereo-endoscopic camera; virtual models of tumors or blood vessels may then be re-projected, in real-time, onto the image of the organ (see Figure 1.24). This solution is intuitive, as it does not require any specific equipment, nor any large modification of the operating procedure. The research results were validated using a silicone liver, and then using real data from patients. They showed that the margin of error between the estimated and real positions of the tumor were lower than current margins of error in surgery. There is, nonetheless, a long way to go before these techniques are entirely validated for routine use in the operation theater.

Figure 1.24. *Different steps in a hepatic surgery, clearly showing the amplitude of deformations of the liver. We can see that despite the significant deformation, the virtual model remains correctly positioned on the laparoscopic image. The images from top to bottom show the different anatomical structures that are easy to visualize or hide, depending on the surgeon's requirements. For a color version of this figure, see www.iste.co.uk/arnaldi/virtual.zip*

1.2.5. *Current conditions and future prospects*

AR has made significant progress in the field of surgery over the last five years, and AR applications are slowly emerging from experimental protocols to be integrated into real-life uses. With reduced surgical risk and shorter hospitalization periods, these new surgical techniques that use VR, digital simulation and interventional imagining, promise to be the future of surgical procedures. However, in order to achieve this, research and development must be pursued, especially with respect to the robustness of algorithms and also the predictive capacity of simulations. There are still only a few practitioners who are working on this topic in France. In spite of this, over 150 operations using AR were carried out there between 2014 and 2017, making France one of the leading actors in this field. Nonetheless, this remains an emerging technology, which still requires more validation and experimentation, as well as true complementarity of competencies from the development of the algorithms up to the surgery itself.

This (r)evolution in surgery and interventional medicine, in the broad sense, resembles the transformation wrought 20 years ago by the arrival of computer programs dedicated to the processing of medical images. Through information processing, numerical computations, visualization and easy manipulation of complex concepts, AR and VR have widened the field of possibilities, which in turn has led to the development of connected technologies or made it easier to use these technologies. While it is still difficult to state precisely what direction these evolutions will take, we see two fields emerging today: robotics and 3D printing. A central element in robotics is the control loop, which consists of a set of algorithms that process data in real-time in order to give the right commands to the robot. This control is often based on the analysis of images from one or more cameras. We then speak of a visual Master–Slave setup. This becomes very complex when the robot has to interact with soft tissue, for instance, during the insertion of a needle in a tumor. A direct link is then established between the AR and robotics systems, with the surgeon being able to define the optimal positioning for the needle via a planning phase. Thanks to a real-time simulation, the surgeon can then control the robotized needle through the AR. Hence, 3D printing has sparked off much interest among surgeons – it allows them to create objects that can easily be manipulated in 3D and are faithful to the patient's anatomy. The projection of the virtual model onto the physical model of the organ will soon offer surgeons new possibilities of tangible interfaces. [FRE 14].

Regardless of the case, as its name indicates, the purpose of assisted surgery is to help the surgeon carry out the operation and make decisions, but it can never replace them. The surgeon must remain the main decision-maker and actor.

1.3. Sustainable cities

What are the VR-AR applications that have made an impact in the last decade on the urban landscape, and what applications are likely to emerge over the coming years?

The objective of this section is to provide some answers to this (vast) question. We have chosen to do this by focusing on three main axes:

– traveling and, more specifically, mobility aids in an urban setting;

– buildings and, more broadly, architecture;

– the city and, more broadly, urbanism.

1.3.1. *Mobility aids in an urban environment*

The omnipresence of outdoor navigation tools, associated with an increasingly precise map of the world is, by now, well established. We can also see that precise urban cartography is no longer exclusively the domain of the technical services of a city's administration; the considerable developments in this field over the past 10 years are the result of work by industrial giants (e.g. Google, Apple, Microsoft, Tom Tom, Mappy, Here; see Figures 1.25, 1.26 and 1.27).

Figure 1.25. *Google Maps: 2D map (© Google Maps)*

2D and 3D visualizations are present in more and more applications meant for general use (e.g. Google Maps), which can guide the user to a location by marking a route that the user may not have known about before. These applications often offer us additional information, for example, pointing out the geographical location of points of interest (e.g. food, culture, business) along the route or close to our destination. The user may not always be interested in these points of interest, but they often show up because the advertising can finance part of the development of these tools.

Figure 1.26. *Google Maps: 3D view (© Google Maps)*

Figure 1.27. *Google Maps: Streetview (© Google Maps)*

Given the difficulty of reading maps that are too often abstract (many people have difficulty reading a 2D map), AR was soon seen as a good answer to this issue of facilitating mobility [KIM 06, KRE 10]. It enables the user to visualize a path that is superimposed onto an image of their real, observed environment on a smartphone or a tablet (see Figure 1.28).

Figure 1.28. *AR application from Here indicating the route to follow (© Here)*

Moreover, AR has made it possible to overcome the main constraints of a good navigation assistance tool, namely making it easy to read the map and identify locations without endangering the user (pedestrian, cyclist or motorist) by giving them too many difficult cognitive tasks such that they pay less attention to possible risks in their environment.

Thus, maps on a mobile terminal have rapidly developed over the past 10 years [SCH 07]. The increasingly realistic 3D visualization of information, coupled with GPS capabilities of locating the user and orienting the view of the map based on their direction of travel, were key factors in this strong growth.

While we wait for the advent of driverless cars, there is an alternative to using these mobile terminals in vehicles: visualizing these images overlaid on the windscreen, so that our eyes are always on the road. Indeed, looking away from the road to focus on the navigation device distracts the user and consequently increases the reaction time if we need to react unexpectedly. We thus talk about "Head-Up Display" (HUD). These have long been in use in aviation (first military and now civil aviation) to visualize information in the cockpit. These systems were developed many years ago by automobile manufacturers and outfitters; the only reason they are currently restricted to a few vehicles, usually high-end vehicles, is because of the marketing strategies used. It is clear that these devices will become more generalized in the coming years [YOO 15].

However, one challenge remains to be addressed before these AR applications can be widely adopted: that of anticipation while driving. In effect, in GPS tools for cars, changes along the route (turning at an intersection, for example) are announced and visualized in advance. This allows the driver to prepare themselves, by replacing their current point of view with what they will see a few dozen meters ahead. In AR applications, where visualization is centered on the user's current position, it is not possible, at the moment, to anticipate this change in point of view. This situation is not problematic for pedestrians as they are travelling at low speeds that enable them to react in real time, unlike users in automobiles, travelling at much higher speeds and where anticipation is absolutely essential. Another illustration of this vision centered on the user's position: is it more effective to view nearby shops in AR (see Figure 1.29), or on a map, in order to correctly gauge the relative spatial distribution?

This problem can be addressed using existing 3D databases to alternate between user-centered vision and a more general perspective (aerial?), which facilitates anticipation and the viewing of nearby information.

Figure 1.29. *An AR view showing Points of Interest (© Nokia Live)*

Another challenge is the management of masking, due to the unique two-dimensional character of the images, which are displayed with no depth information whatsoever. Consequently, it is sometimes very difficult to determine whether an element is situated in front of or behind a building, for example. In an urban context, where there is a high density of buildings, this difficulty in accurately perceiving the environment hampers the greater development of AR applications. As depth-capture tools are available, the question then arises as to which method must be used to visualize this information in a way that will be optimal for the user.

1.3.2. *Building and architecture*

When it comes to sustainable urban systems, we are more specifically interested in devices that make it possible to study, present and co-construct the city. As the city is composed of buildings, among other structures, there is an obvious link between the city and architecture.

Synthetic images used in architecture have evolved considerably over the last decade (see Figures 1.30 and 1.31), most notably due to the progress made in visualization algorithms, as well as modeling software, both professional and for general use. However, it is the insertion of elements from daily life which have seen the most spectacular progress over the last five years. Given the number of characters and decorative elements, even the image of the building tends to disappear behind the narrative of the life around it.

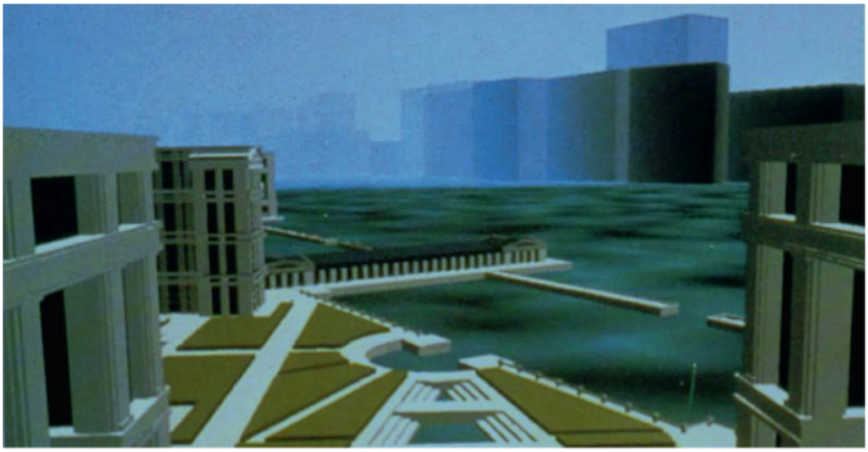

Figure 1.30. *Old synthetic image (© Archivideo)*

Figure 1.31. *Modern-day synthetic image (© Kreaction)*

Figure 1.32. *Virtual reality outdoors (© Rennes Métropole)*

Figure 1.33. *Augmented reality associated with a ground-plan (© Artikel)*

The use of AR for architecture still remains rather anecdotal today and is often limited to overlaying a 3D representation of a building onto a ground plan. Beyond the initial excitement experienced, we may legitimately wonder what real benefits this type of representation can offer with respect to the "classic" visualization of a 3D model of the building, which offers internal navigation. Moreover, the use of AR outdoors [ART 12] poses the same problems as the use of mobile navigation tools, but even more acutely, as concerns geo-positioning and mask management.

VR, on the other hand, has offered architecture a host of tools to play around with almost from its first appearance on the scene. Many architects dream of "Walking around" in a future building [CHI 13], which in reality may still only be at the blueprint stage. Already sensitive to multisensory perception (sight, sound, touch), professionals in the field of architecture are an ideal audience for VR. It must be noted, however, that even though there are frequent references to the use of this type of application, they are often only anecdotal. Other than the financial barrier, which may be removed by reducing the large cost of the VR equipment (headsets and large-screen immersive systems), the main obstacle to development is more cultural than anything else! The fact is many architects believe that it is difficult for a client to understand an object that is yet to be completely finalized; they thus use VR only for the final presentation of the project, focusing on a high degree of realism. This restricts the use of VR to a communication tool reserved for large projects. At the same time, some architects or "high-end" promoters are reluctant to use this as the headset cuts off visual contact with the client, which is essential in a sales pitch. One solution to this may be to introduce the architect in the VR application in the form of an avatar.

This situation is now evolving, thanks to the increased use of collaborative work at different stages of construction design, as well as in the creation of models that are more and more refined and easily updatable. These innovations, jointly called BIM (Building Information Modeling) [SUC 09], are key elements in the use of VR in architecture. More specifically, BIM was presented by Eastman *et al.* [EAS 08] as a new approach to design, construction and the management of installations, in which a digital representation of the construction process is used to facilitate the exchange and interoperability of information.

It is interesting to analyze the use of 3D, and potentially VR, among interior design vendors (e.g. bathrooms, kitchens; see Figure 1.34). This profession has quite rapidly progressed from 2D diagrams to interactive 3D representations. The reason for this is quite simple: a sale is facilitated when all of the members of the family that will invest in this equipment commit to the idea. The limitations in the use of the 2D plan were quickly revealed. However, the immersive visualization makes it possible to heighten the client's acquisitive impulse. It is therefore not surprising that these professions are among the leading users of VR, thanks especially to the new low cost equipment which has recently appeared.

Figure 1.34. *Ixina Kitchen (© Ixina - Dassault Systèmes)*

1.3.3. *Cities and urbanism*

Contrary to the widespread idea, nurtured even by certain professionals, the technological approaches adopted for urbanism are not the same as those used in architecture. While a city is made up of buildings, their digital models (and thus, the modeling methods used to construct them) are very different. Today, it is easy for someone who has one of these software on a standard computer to create a realistic model of a building and to obtain an interactive visualization; they may therefore imagine that they can do this with many buildings, to construct an island, then a neighborhood and then a city. Unfortunately, this is a false belief. First of all, there is the question of complexity: the difference in scale is not a "reasonable" one for an urban environment made up of dozens, hundreds or even thousands of buildings. Second, the impact of the increase in the size of the digital data is not linear -

there are thresholds (especially those related to the volume of available and effectively usable memory on a computer) that limit the use of certain software solutions. Finally, and most importantly, a city is not made up only of buildings but also has other objects of different and complex natures and may even be invisible (e.g. roadways, signage, networks that may be underground). Furthermore, the scale of reading the city may vary a lot: from a macroscopic view to analyze road traffic problems or study urban strategies (city planning), to a view centered on a single building, similar to that used in architecture (urban design).

All of these factors explain why complete modeling (see Figure 1.35) is not yet widespread and why we often restrict ourselves to taking into account only the neighborhood around a specific project.

Figure 1.35. *Image in an immersive room (© IRISA)*

Even though the digital urban data sometimes has a third dimension (height), the old-fashioned software used to model and visualize the city are constructed using a planar approach (2D), which limits their use to approaches that can more appropriately be called 2.5D. This is due not only to technical simplifications (e.g. optimization of the display on the ground, the use of planar projection), but also to the established culture of using a 2D map.

Despite the fact that this technique has existed for a long time, orthophotography has only really become popular in the last few years thanks to applications such as GéoPortail, Google Maps and Google Earth. These applications are based on the display of aerial photographs whose geometry has been modified so that they can be associated with geo-referenced earth tiles that pave the surface of the region. For a 3D representation of the city, this visualization (called "oblique aerial imagery") is by far the most widely used, as it allows the user to easily perceive the environment, or the program in the case of a project [KAA 05] (see Figure 1.36). This perception makes use of a decoding process that is based largely on the imagination: we have all seen (in the cinema or on television) similar visual sequences, even though we have never been in an aeroplane.

Figure 1.36. *Data base from aerial data (© Rennes Métropole)*

If we want to have a truly immersive view of an urban environment, we have to adopt a different modeling method. In effect, all users have had experience as pedestrians, where vertical elements (buildings, sidewalks, signposts, vegetation) play quite an important role in the processes of perception and positioning of oneself.

The reconstruction of a city in this way, for an immersive visual experience (see Figure 1.37), is still far from being completely automatic. In fact, the people who build these virtual cities dedicate a great deal of time to ensuring that there is coherence between elements that cannot be automatically processed using existing data, generally taken from Geographic Information Systems (GIS) and used mainly by local administration (e.g. land registration, networks). Obtaining flat roads, integrating bridges, or even worse, interchanges, erasing traces such as the impression of trees along the routes or on the buildings (resulting from the orthophotography or from images taken by a mobile scanner): all these and more pose so many obstacles that they cannot all be processed without eventual human intervention, which is quite demanding and not at all easy. The result of this processing is that the production of cities for visual immersive experiences is still quite financially heavy and the return on investment is hard to estimate.

Figure 1.37. *A virtual Paris, Archivideo (© Archivideo)*

This latter observation may seem inconsistent with recent evolutions in the urban databases produced by Google or Apple using massive correlation algorithms (see Figure 1.38). We must remember that these applications, which produce visual results with an excellent degree of realism, use orthophotography primarily and not 3D databases. If the user exits the aerial view and wishes to “come down”, visual aberrations soon start appearing. Hence, these applications forbid trajectories that are “too low”. In order to remove these restrictions on navigation, Google Streetview uses a database of photos that are not taken from an aerial view, but from the ground in specific photographic missions (using vehicles equipped with cameras and GPS systems) to offer an exhaustive coverage of all the streets in a city. This application then proposes a 360° view, from a specific point in a street, of all the surrounding buildings. The view is captured so as to be at eye-level for an average pedestrian on that spot.

Figure 1.38. *Google Maps (© Google Maps)*

We must, however, specify that these views do not really qualify as VR. They are, in fact, based on photographs taken from precise points and thus cannot respond to a user's desire to move around freely (to go into a garden, for example). Thus, they cannot be re-oriented or extend to suit a user's desire to move freely. The difference can be explained quite simply by recalling that VR is based on the real-time computation of synthetic images from any point of view and in any direction, thanks to a 3D model which gives the user total liberty, as opposed to applications based on photos.

Finally, let us specify that this distinction is by no means a value judgment: each approach has its own advantages and disadvantages. These are often complementary, depending on the desired objectives and available means.

1.3.4. *Towards sustainable urban systems*

Let us return to the heart of the question we posed at the beginning of this chapter. Going beyond purely technical considerations and the barriers that must be removed, what are the functions that we would wish to develop for VR-AR in the coming decade in the case of what are called sustainable cities? We can state three distinct uses:

– The first use is directly related to the communication tools used for the project. Even though this observation is not very old, it is now commonly admitted that 3D visualizations are more effective than a map and, above all, that they are more useful in a presentation. Urban specialists today often wish to communicate their projects to a population that has little or no technical expertise, such as elected officials or citizens. The challenge here is to put across the project clearly and avoid errors in interpreting the information. VR-AR can then be brought in from the user's point of view. Given its limited aspect, the representation can easily shift from the user's point of view (what they perceive) to the project details (how the project works).

– The second use is a consequence of the opening up of technical services within communities. This is done to avoid the effects of working "in silos", where each expert addresses their own problem without engaging with the collateral effects on other projects. Collaborative work around a common and enriched model of the city is starting to take shape for designing, realizing and maintaining the city more efficiently. The pooling of technical knowledge can be made easier by the use of shared immersive viewing in VR during a project review (as we have already seen happening in other sectors – e.g. manufacturing industries, sciences). As for AR, it is likely to see considerable evolution for use in the maintenance of public spaces.

– The third use is related to the first and arises from the fact that some municipal administrations wish to co-construct the city with their citizens by giving them the option of participating in the definition and development of projects. They are asked, "What kind of city would you like to see, in terms of renovation, layout and transport?". Successfully adopting this procedure requires that certain questions be addressed. Those in the "upstream" phase are how to present the problem, and the possible scenarios. In the "downstream" phase they are how to list and summarize citizen suggestions. It is clear that VR provides part of the answer, as it allows a heterogeneous group to visualize an urban environment at the same time and in the same place; it then allows the visual simulation of the object in question (e.g. adding a new building, modifying a transport line) so as to facilitate a collective debate on the issue.

We hope that the arrival of low-cost VR technology, in association with generalized applications that allow the handling of urban data, will usher in a new era of dialogue between the city and its citizens. The example of experiments such as RennesCraft (see Figures 1.39 and 1.40) or the layout of the eco-friendly neighborhood, Niel, in Bordeaux can be viewed as being emblematic of this process.

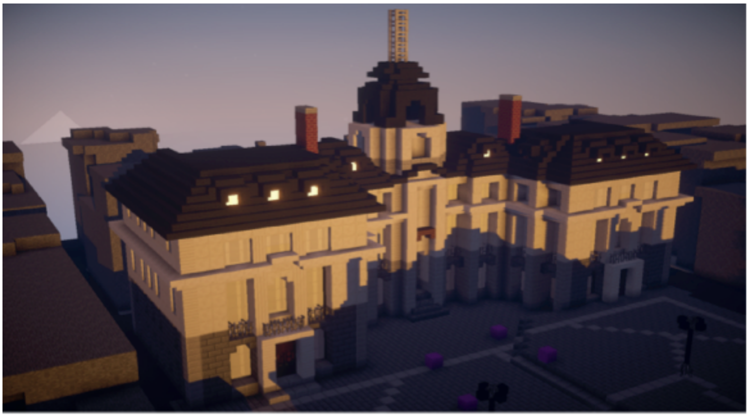

Figure 1.39. *RennesCraft (© Rennes Métropole - Hit Combo)*

Figure 1.40. *RennesCraft (© Rennes Métropole - Hit Combo)*

1.4. Innovative, integrative and adaptive societies

It must be stated that the impact that VR-AR have had on society is far from negligible. Section 1.3 focused on sustainable cities: by definition, these include a social component. The rest of this chapter is dedicated to two specific fields of application where VR-AR can participate in evolution in our societies: first of all, through education and then through arts and culture. These domains have already been discussed in [FUC 05], but uses have developed considerably since then and we think it is important to revisit these topics.

1.4.1. *Education*

1.4.1.1. *Context and history*

There are many advantages to using VR in a teaching (professional and academic) or training context, which are described in detail in [BUR 06, LOU 12]. To name a few: the removal of risk to humans; the use of material that is rare or difficult to access, as well as cumbersome and/or costly; an ability to recreate situations that may be complex; a reduction in costs; availability of equipment; and, finally, being able to control the learning environment/situation. Group learning using VR can make it possible to overcome the problem of having collaborators available, thanks to virtual humans. It is also possible to bring in remote participants or moderate the behavior of fictional coworkers. VR also makes it possible to very realistically reproduce elements of real life [BUR 06, LOU 12]. The simulated system is assumed to react like the real system it represents, so as to give the learner an understanding of certain aspects of the experience, which they will then be able to draw on in real-life situations. At the same time, these situations are much more flexible than real situations (e.g. the ability to modify the situation, the simulation of rare conditions, controlling specific parameters, the reusability and adaptability of scenarios, reversibility of actions, ability to monitor learners).

Often used for training in situations that are very close to the real situation, virtual environments do not always offer pedagogic control. When functionalities for control and monitoring are available, it is possible to personalize the content for each learner by offering them the most relevant situation (progression along the learning path, remediation of errors, reflexive approach, etc.). In order to control and adapt situations according to the learner's needs, the following points can be considered:

– Diagnosing erroneous concepts and dynamic learner profiling: the general idea is to be able to detect erroneous behavior and then to try and associate this behavior with errors in knowledge or the wrong application of this knowledge. This type of approach is often implemented by smart trainers [BUC 10]. Two types of approaches can be used to diagnose errors: the generative approach and the evaluative approach. The generative approach consists of generating the solution to the given problem as well as certain typical errors and then comparing this with the solution given by the student. These steps are not always sufficient to determine the type of intervention to be carried out, and their ability to explain behavior remains rather limited. The evaluative approach is based on what is called the "constraint-oriented" approach, where the trainer verifies how far the learner respects certain conditions. This type of approach is well adapted to diagnostic tasks but is less useful for procedural tasks where respecting an order is primordial. [LUE 09] proposes alternative methods of diagnosis, based on an epistemological model of knowledge of the subject, which examines actions and the reasons behind these actions (in themselves, and not relative to an expected solution). The error is considered a symptom of the knowledge.

– Assistance: assistance or feedback may be offered to allow the learner to adopt reflexive learning (i.e. allow them to reflect on the task and their learning). We can make use of certain functionalities that VR offers (slowing down the scene, speeding it up, changing the point of view, looking through obstacles, visualizing processes that are not accessible to our senses, asking for sensory reinforcement or substitution, concretizing abstract concepts). We can define two kinds of assistance based on whether they occur within or externally to the situation: intra-diegetic and extra-diegetic [CAR 15].

– Controlling the scenarios: this has to do with deciding on and orchestrating the situations and narrative that will allow the student to learn better (verification of acquired skills, reinforcement of skills and development of new skills). Controlling the learning process often means that there is no adaptability. Freedom of action is not compatible with control and trying to marry control and adaptability can risk bringing in incoherence, and so on [BAR 14]. We talk of the narrative paradox when discussing the fundamental opposition between interactivity and narration: giving the player a greater capacity for action will interfere with the script prepared by the author.

Variability in scenarios is sometimes achieved only at the cost of a great deal of design work, where all possible deviations must be explicitly, manually described. The effort needed to bring in coherent and precisely controlled scenarios is called an authoring bottleneck [SPI 09]. This highlights the necessity of putting in place scriptwriting systems that make it possible to create easily adaptable environments. However, it is quite frequently the case that systems stop applying an overlayer of control on a simulation composed of independent entities, and that interventions by these systems will disrupt the coherence of the environment by modifying the simulation states on the fly. There are two ways of overcoming this problem: scenario-oriented approaches (which steer the virtual environment at the global level) and independent virtual-character-oriented approaches, which bring in scenarios based on the behavior of the user and the virtual characters. The scenario-oriented approaches emphasize the overall quality of the scenario (a complete overview of this is given in [CAR 15]). The complete description of all possible scenarios in the simulation must be defined. There is thus complete and centralized control over the simulation. The level of guidance may, however, vary from completely guided, to total freedom for the user. These narrative models are mainly based on specific representations of the 3D environment which make it possible to enrich the geometry of objects through higher level information: informed environments (smart-objects or objects-relations models). In the other, character-oriented approaches, the narrative is built out of the interactions between the user and the virtual characters that populate the environment. Control is distributed and each character is responsible for their own decision-making. These approaches are focused on the creation of cognitive virtual characters (a comprehensive introduction to this can be found in [BAR 14]).

In reality, a very fine line exists between these two approaches, and several parameters must be taken into account, such as the production of scenarios in a static manner (scripted approach), or a dynamic manner (generative approach), or even whether the control is centralized or distributed. Finally, most approaches use a hybrid of these two orientations to address the above-mentioned problems. Examples of these are Thespian [SI 10] and Crystal Island [ROW 09].

1.4.1.2. *Scenario models: two examples*

In this section, we describe two platforms that use a hybrid approach to control scenarios: the character-oriented HUMANS and the collaborative, virtual-environment-oriented #(FIVE,SEVEN) with a pre-defined scenario model.

Figure 1.41. *HUMANS: character-centered approach (© EMISSIVE)*

1) The HUMANS (Human models based artificial environments software platform) approach, a character-centered approach, is a system used to create varied situations; it is highly dynamic, subject to random and sometimes critical errors, whereby there are situations with no ideal solutions. HUMANS has set of objectives that often seem contradictory: freedom of action for the learner, allowing them to learn through errors; a dynamic nature and effective control over the scenario to guarantee learning; consistency in the behaviors presented in order to make the system self-explanatory; and, finally, the adaptability of the system in order ensure the variability of the scenarios. The virtual characters are independent in order to allow the system to be adaptable. They have emotions, diverse personalities and social relationships. They have "human" behaviors and can compromise, transgress safety regulations, commit errors, disrupt or facilitate teamwork, etc. [HUG 16, CAL 16]. In order to control the learning situations and preserve the coherence of the world, a scenario-generating system must indirectly orient the unfolding of events by occasionally modifying conditions governing the virtual world or the virtual characters, without giving them orders [BAR 14].

A scenario-generator uses the learner's activity traces to diagnose their dynamic profile [CAR 15]. This profile operationalizes the zone of proximal development (ZPD), described by [VYG 78]. A vector space of the class of situations is associated with the values of belief in the ability of the learner to manage the situations that they describe. The engine selects the objectives of each scenario in the form of scenario spaces in the ZPD. Based on the learner's results, the engine selects situations in the proximal zone or extends this zone. Moreover, it determines the objectives in the form of desirability values in specific situations and general restrictions on the properties of the scenario (e.g. complexity, criticality). By using the models underlying the simulation, the scenario-generator predicts the evolution of the simulation using a planning engine [BAR 14]. It calculates a scenario based on these predictions and a set of possible modifications. Three types of changes can be used to ensure coherence: triggering exogenous events that have no relation to the coherence of the system, late commitments (this principle makes it possible to progressively specify, during the simulation, states that were left uncertain at the initialization) and co-occurrence constraints (forcing stochastic behaviors). If the actual scenario deviates from the planned scenario, the engine plans a new scenario. HUMANS has been deployed in a variety of training applications: risk-prevention, aeronautics, rescuing injured persons, etc.

2) The #(FIVE,SEVEN) approach proposes a reactive, collaborative environment with a pre-defined scenario model (Figure 1.42). A VR application is defined with the help of several components, among which is a model of an informed environment and a model of scenarios. STORM [MOL 07], a generic objects-relations type model, was proposed. Later on, a new generation of a reactive, collaborative informed environment, #FIVE (Framework for Interactive Virtual Environments) [BOU 15], was proposed. This model makes it possible to describe and rationalize objects, which may participate in an action (and actions may use objects) using requests. In parallel to this, LORA [MOL 06], a single-user, scenario specification language, based on parallel hierarchical finite state machines, has been proposed. In this, actions are represented via the STORM model. This was extended to collaborative scenarios using LORA++ [GER 07]. However, the interaction with the environment beyond the action of the actors is not immediate and the environmental model is fixed.

Figure 1.42. *#(FIVE,SEVEN): Approach centered on using predefined scenarios (© IRISA)*

The scenario model #SEVEN (Scenarios Engine for Virtual Environment) [CLA 14a, CLA 15b] was developed to address these limitations. It represents the complex temporal layouts possible for the technical and procedural events of the simulation. It is based on the Petri network and is enriched by sensor-effectors that connect it to the environment. It is compact, expressive, independent of the field of application, collaborative with multi-user management (real or virtual users) and implements a model that uses dynamic roles [CLA 15a]. #SEVEN was also designed for use by industry experts who are not software engineers and has an offline editor and online events generator. Productivity is essential for designing a VR application. #FIVE makes it possible to independently define objects and interactions in the informed environment, which may be done in the form of activities. #SEVEN describes the set of possible solutions in a compact manner with an author tool for editing and is independent of informed environment models. We have, however, proposed a coupling between these two models.

When we want users to be interchangeable (i.e. the users may be virtual humans or real humans) [GER 08], these models must abstract and trivialize the collaborative interaction with the objects for the actors (virtual and real). The Shell concept [LOP 13] was introduced: an abstract entity connecting an actor (real or virtual) to the virtual world, in order to allow the actors to exchange roles via a protocol [LOP 14], while also guaranteeing the continuity of actions and the gathering of knowledge.

These models and concepts are used in varied domains: industrial, medical and cinema. [BOU 16]. They are under study for use in the area of cultural heritage.

1.4.2. *Arts and cultural heritage*

Art and cultural heritage are particularly apt areas for the development of innovative methodologies related to interaction and immersion. VR and AR make it possible to combine advanced technologies based on images, sound and multimodal interactions to plunge the user into artistic or cultural experiences that enhance user experience (UX). 3D printing further opens up the field of possibilities by offering supports for visualization and interaction that were hitherto unknown. The user can thus become an active part of a work of art or experience learning through an immersive scientific mediation. The user can also be a historian or archaeologist interacting with a physical and/or virtual representation of the object they are studying, which can allow them to collect new information from it.

1.4.2.1. *Performing arts: dance*

For computer engineers, it is possible to “use” dance and dancers in case studies and for experimental environments. The artists’ creativity leads them to formulate needs, which then orient research in VR and AR and help advance these technologies. Where the dancers are concerned, this science is in itself a world to be explored through their art. The questions the computer scientists ask, so as to model the context of the interaction, lead the dancer-choreographer to revisit the fundamentals of dance. Finally, developing these technologies offers the dancers new artistic tools with which they can explore virtual worlds.

AR provides an ideal framework with which to negotiate this joint research, as can be seen in the brief discussion below, starting with the work that laid the foundations of this domain.

One of the precursors to this, which began in 1998, is Hand-Drawn Spaces, a performance created by the famous innovator and choreographer Merce Cunningham, in collaboration with Paul Kaiser and Shelley Eshkar from the company Unreal Pictures. This performance, presented during the international conference SIGGRAPH’ 98 [KAI 98], was a landmark moment in dance and motion capture: there is a virtual landscape with three screens and hand-drawn figures; dancers appear in the form of full-scale designs. 2002 saw the première of the Jew of Malta at the Munich Opera Festival in Germany [SAU 02]. This performance, which was located within the AR paradigm, was a co-production between Büro Staubach of the Opera Biennale

Munich and the ART+COM studio: it combined architecture and costumes generated in real time, depending on the music and the singer’s position on the stage.

Experiments of this kind were seen in France from 2006 onwards, starting with the Lyon contemporary arts Biennale, which associated dance and technology. 2013 saw “M. et Mme Rêve”, a performance that was emblematic of the marriage of engineering and the Arts, produced by “le Théâtre du corps Pietragalla-Derouault” in association with the company Dassault Systèmes. This was a performance where dance and 3D technology met on stage to transport the spectator into a unique, 3D virtual reality experiment. In 2009, the concept of an “augmented dance show” was demonstrated for the first time, combining ballet and AR. Then there was the “festival les Ethiopiques” in Bayonne, which in 2009 and 2010 offered enhanced improvised performances that combined dance, music, readings and a virtual world [DOM 09, CLA 10a]. In 2010 again, there was the festival “Le Temps d’aimer la Danse” (A Time to Love Dance), which laid an emphasis on performances that allied digital art and dance, like Gaël Domenger’s creation “Un coup de dés jamais n’abolira le hasard” (Dice Thrown will Never Annul Chance), a tribute to Mallarmé and his typographic poem.

In these creations, the objective is to allow the artist to create a virtual world on the stage, a world in which they can evolve and create their art, making their process of creation and its result visible to the audience. In effect, earlier performances were limited to the projection of virtual content onto the stage. What was needed was being able to generate and animate 3D images using the hands and the body, within a vast space, while also allowing other people (here, the audience) to participate in these transformations. One of the major challenges that has been addressed in these performances is allowing the creation and animation of virtual objects projected in real time [COU 10, CLA 10b, CLA 12] (Figure 1.43). The dancer controls the virtual world by not only manipulating pre-defined virtual elements, but also creating them by using their hands to generate the visual material. The dancer thus becomes a sculptor and their gestures and movements become frozen in time; the sculpture creates a work of art, but the movements that lead to that creation are sublimated into a choreography [CLA 14c, CLA 14b].

From 2016 onwards, the Kinect position sensor from Microsoft has been widely used in the creation of dance performances, as it allows a basic visualization (pixelated), which is very well adapted to artistic rendering (see [KEN 16, FIS 16]). The living performance is enriched by VR: for example, "TREEHUGGER, a virtual reality experience" [MAR 16] or even "l'Arbre Intégral" [GAE 16] (Figure 1.44), and many other artistic experiments created using "augmented performances" [SIT 17].

Figure 1.43. *3D-augmented Ballet, Biarritz, 2010 [CLA 12] (© Frédéric Nery)*

Figure 1.44. *L'arbre Intégral (The Integral Tree) (2016) [GAE 16]*

In conclusion, as demonstrated by the works mentioned above, art and engineering are no long separate; the division between them has become porous, and they mutually enrich each other. This is a trend that is most certainly going to continue, both in France and other countries. In the United States, for example, this will be through the school of thought called "from

STEM to STEAM" (STEM for Science, Technology, Engineering and Math; STEAM for STEM + Art). This combination is also a reality in the case of the worlds of computer science and cultural heritage.

1.4.2.2. *Cultural heritage: archeology*

Both VR and AR offer new perspectives in the field of cultural heritage and, more specifically, in the field of archeology.

1.4.2.2.1. Cultural heritage and virtual reality

VR can quite naturally be used as a support with which to implement tools and working methods for archeologists [FUC 06] (pp. 229–233). Introduced a long time ago, notably by Robert Vergnieux, interactive simulation makes it possible to reproduce and validate gestures and to establish the physical coherence and technical feasibility of reconstructions [VER 11]. Since then, Pujol Tost *et al.* [PUJ 07] have argued that archeology must take into account interaction and perception as well as VR simulation, rather than focusing only on the visualization of 3D models. The importance of perception is notably illustrated by Le Cloirec [LEC 11] through the use of 3D reconstitutions in immersive structures in order to evaluate the functional or symbolic roles of the architectural elements and spaces being studied. A scale-1 functional and interactive reconstitution of an environment, such as a ship (Figure 1.45), allows the historian or archeologist to become the actor in the simulation [BAR 15].

Figure 1.45. *An interactive reconstitution of The Boullongne, a 17th-Century ship (© Inria)*

The unique features of archeology often pose particular problems for VR. First of all, we must recall that the reconstitutions of sites are based on the observations of fragments and on hypotheses proposed by experts. If we wish to ensure that these models are credible in any way, it is absolutely essential to take into account this uncertainty surrounding the hypothesis, both for the reconstitution process and for the final restitution, working closely with the archeological expert [APO 16]. This consideration is often ignored in the 3D reconstitution of antique monuments that have been destroyed (temples, habitations). These reconstitutions are widely diffused (over television or the web) and offer highly realistic renderings, close to those in video games, for example. As human perception is highly sensitive to visual details, it is nearly impossible for a non-expert user to distinguish between reality and details imagined up by the authors of these images. In other words, there is an ethical responsibility involved that is often forgotten in these applications.

Furthermore, archeological sites, by definition, are ancient and therefore have evolved over time (sometimes significantly). Here again, a dynamic and interactive representation of the changes is required. This is so that they can be better studied by the archeologists, on the one hand [LAY 08], and non-expert users can understand them, on the other hand.

Both these characteristics (uncertainty and change) are unique to archeology and are not found in other fields where VR is used, such as an industrial setup, where the objects studied are “stable”. Hence, researchers must invent specific modes of representations that are adapted to this particular context.

The interaction with archeological objects also poses certain unique problems when compared with the objects that are usually encountered in other domains where VR is applied. The artifacts that archeologists study are often closer to nature than manufactured objects encountered in industry, for example, which implies a greater complexity in the geometries to be manipulated [BRU 10, PAC 07]. Additionally, these artifacts may be inaccessible without a destructive analysis. The 3D printing of reproductions enables a tangible interaction with the object (Figure 1.46), while preserving the actual archeological artifacts [NIC 15].

Let us also specify that the proprioception and motor skills of a user in VR allow them to reproduce and better understand certain technical gestures from the past that have disappeared today [DUN 13]. Finally, archeologists are also able to preserve a visual trace of their reflections by adding annotations to the digital model [KLE 08].

Figure 1.46. *Interaction with a tangible object: the gallic weight (© IRISA)*

1.4.2.2.2. Cultural heritage, augmented virtuality and spatial augmented reality

Augmented virtuality (AV) consists of including real physical information in a virtual world. By construction, VA is the paradigm of Tangible Interfaces. In effect, the task is situated in the virtual world and the user acts on digital information by manipulating physical objects that represent either the digital information or a control on the digital information or both. An interactor is the abstraction of an entity that is capable of both input and output in an interactive system. Consequently, the interactor is a mixed object that possesses both physical and digital properties and the computer system connects these properties. An example of AV in archeology is ArcheoTUI [REU 10], which is based on the concept of bi-manual interaction and allows efficient interaction for the manipulation and assembly of archeological fragments, which have been digitized into 3D beforehand (a bit like a 3D puzzle). Automatic matching techniques are also possible [HUA 06], but their performances are still limited. It would therefore be interesting to be able to offer archeologists a system that makes it possible to combine purely manual assembling with automatic assembling, as in the work carried out by [MEL 10] as part of the ANR SeARCH project, motivated by a clearly defined archeological project: the partial reconstruction of the lighthouse at Alexandria and the statues around it.

Spatial Augmented Reality (SAR) is based on projective displays. It uses projectors that make it possible to directly display virtual elements onto real objects. They offer a strong potential for introducing new techniques for interaction. This is because the co-localization of the space of perception and the space of interaction in the real world make it possible not to upset our spontaneous habits of interaction. For example, direct interaction using our hands. An example of SAR in archeology is the development of a "magic" virtual torch, a revealing flashlight [RID 14]: this is an interactor with six degrees of freedom, meant to enhance the visual analysis of a real object by the overlaying of digital information using projection. This interactor, a tangible surface as per Fisckin's classification [FIS 04], refers to a flashlight with three metaphors: the zone to be inspected is determined by the position/orientation, the angle of inspection (characterized by the direction) and the intensity of the visualization (determined by the distance). Thanks to the object being digitized in 3D form beforehand and a multi-level geometric analysis of the surface, the real object is augmented with expressive visualization that reveals details on the object that are sometimes invisible to the naked eye, such as curves of different scales, and along different angles. This interactor has notably been used on an Egyptian stele (headstone), the inscription on which was almost completely lost, and the interactor made it possible to improve the legibility without losing the link between the real object and abstract information.

1.4.3. *Conclusion*

By shedding light on these technologies, which are often ignored, a larger field of application for training is likely to emerge in VR-AR, as these allow the learner to actively participate in the learning (changing their point of view through gesture interaction, etc.), adding significantly to the learning process.

The research in the field of interactive storytelling and in ITS (Intelligent Tutoring System) today overlap with the work carried out in VR and, in the coming year, it will enrich content and models. Taking into account certain psychological characteristics, such as emotion or interest, and motivation of the learners, will enable personalized adaptations of the most relevant content.

There are also multi-disciplinary research projects, which must be carried out to demonstrate the pedagogic effectiveness and ecological acceptability (in the situation) of these virtual environments for human learning [LOU 16b].

For Spatial AR in large spaces (e.g. augmented ballets), we must also take into account the question of the spectator's point of view. How do we construct a virtual image, so that it is equally meaningful from different points of view? Does this not imply that we must construct different images depending on these points of view? One path forward is to work on the differences in perception and use this to orient the procedure to follow, combining art and science to respond to this problem.

Finally, VR also offers a real opportunity to create new practices and tools for professions related to cultural heritage and to thus promote access to new knowledge. It can also be used as a first-order support to help in the conservation of heritage; as a vector for adding value and sharing reconstitutions and 3D digitization of sites in danger (whether due to natural wear and tear, urbanization or their geographical location exposing them to seismic risks, wars or the consequences of global warming). As concerns AR, creating a better targeted learning experience is a real challenge and one that many promising research projects are working on. [LOU 16a, CIE 11, LEC 16].

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