Università degli Studi di Padova

Dipartimento di Fisica e Astronomia Galileo Galilei

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Exploration of the Moon between communication and science

PhD Candidate

Biagio Ambrosio

Supervisor

Caterina Boccato

INAF-OAPd

Coordinator

Ch.mo Prof. Giovanni Carraro

University of Padova

Co-supervisor

Dr. Gabriele Cremonese

INAF-OAPd

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Contents

1 Introduction

The goal of this research is to characterize the potential of extended reality technologies, specifically virtual reality, in the context of public engagement. The research was conducted with a proactive approach, as it was not limited to studying the effectiveness of existing extended reality products but instead a considerable portion of the research activity was devoted to the development of an innovative product, based on scientific contents, to be subsequently presented to the public. This allowed us to explore the critical issues related to the development of virtual reality experiences, in order to understand the challenges and opportunities offered by this medium. The primary goal was to develop a product that could achieve a high level of engagement while maintaining a good degree of realism concerning the scientific contents presented and an acceptable level of comfort and enjoyment in terms of experience. The result of this development was the virtual experience MOON RESCUER, in which the user operates within the context of a hypothetical future lunar base camp. The immersion and interactivity that characterize virtual reality allowed the development of a product that is engaging, experiential, effective, and challenging for users. The main target audience for the product developed in this context consists of young adults, who are often attracted to new technologies and interactive experiences. However, the experience was designed and developed with a level of accessibility that allows it to be appreciated by a broader general audience. This research is situated within a very popular field in contemporary science communication. New languages are emerging, and the need to experiment with new communication techniques and new media is becoming increasingly press-ing. In Chapter 2, we present the theme of science communication in a general way, exploring its historical evolution from its origins to the present day, with particular attention to the public engagement model that is predominant today. We demonstrate how this research fits within the context of public engagement and which aspects of this framework were used in the development of the virtual reality experience. In Chapter 3, we describe the scientific context that served as the backdrop for the virtual experience, that of the lunar environment. We explain why this theme was chosen and explore the research being carried out with a view to future exploration. The MOON RESCUER experience is designed to present a series of scientific content based on real studies and projects in an engaging and experiential way. Chapter 4 provides a description of the various extended reality technologies: virtual reality, augmented reality, and mixed reality. The chapter also includes a discussion presenting the reasons that led to the choice of virtual reality for the development of the innovative product created for this research. In Chapter 5, we describe in detail the development of the virtual reality product. We present the device and the framework used for development and provide a detailed description of all the aspects that characterize the MOON RESCUER experience: the scientific concepts and how they were presented, the elements that make up the virtual environment, the narrative structure, and the interactions. MOON RESCUER was tested by the public as well as by members of the scientific community. The results of these tests are presented in Chapter 6. The chapter also contains an analysis of the impact of the experience from both the engagement and communication effectiveness perspectives. The conclusions of the entire research project are presented in Chapter 7.

2

Communication

The word *communication* is used with different meanings depending on the context. In the scientific landscape, communication falls within the scope of the *Third Mission*, and universities and research institutions are increasingly recognizing its growing importance and centrality (Pinheiro, Langa, and Pausits, 2015). The reason is that the relationship between the scientific community and the rest of the world is inherently symbiotic: society provides science with its primary resources - people, tools, goals - and, on the other hand, scientific results bring significant impact to communities. A fruitful collaboration between the scientific community and society necessarily involves sharing needs, strategies, and objectives at various levels (Compagnucci and Spigarelli, 2020). In this regard, communication is crucial to strengthen and revitalize the relationship between the two worlds.

In this context, some lexical considerations are emerging for the definition of the new role that communication is playing in science. On the one hand, the nomenclature 'Third Mission' – specifically the term 'Third' – is under scrutiny as it carries a negative connotation, and there is a growing preference to speak instead of *Research Valorization*. On the other hand, a clear differentiation among terms as *dissemination*, *outreach* and communication itself is now commonly recognized within the scientific community: dissemination refers to the sharing of knowledge among peers in settings such as scientific conferences and specialized journals intended only for professionals; outreach refers to the sharing of science goals, approaches and results with public. Both outreach and dissemination fall within the general sector of science communication but keeping in mind such difference is crucial for the achievement of successful results in this field. In this project, we focus on communication in the sense of connection between science and society as we described in the previous lines and therefore we are not going to explore dissemination.

Since this research project lies at the intersection of astronomy and science communication, it is essential to define what it entails and the perspective with which the project has been carried out. This chapter is devoted to that purpose. In Section 2.1, we present a general description of communication and its fundamental elements. Section 2.2 provides a summary of the evolution of science communication over the centuries, from ancient times to the present. In Section 2.3, we introduce the public engagement model, which has emerged as the most successful approach to science communication in recent years and in which this research project is embedded.

2.1 Communication elements

The word *communication* originates from the Latin word *communis*, which is derived from two terms: *cum* and *munus*. *Cum* is a preposition used to express association, collectivity, and synergy. *Munus* is a noun used to indicate a task, a function, or a goal. This etymological digression helps clarify the goals of communication: to communicate means to share goals, ideas, and aspirations. Therefore, the role of communication is to bring people together and enable them to enhance each other's abilities and knowledge as they work towards their common goals. The basic elements that define the phenomenon of communication, in its simplest form, are: a sender, a receiver, and the content being communicated. Additionally, a shared language between the sender and receiver is essential. As we will see in Section 2.3, reality is more complex than this, as multilateral communication, as envisaged by the public engagement model, involves continuous role exchanges between sender and receiver, as well as a diversification of languages and content. For simplicity, in this description, we will limit ourselves to a unilateral presentation of the different elements, assuming the following framework: within the scope of the project presented in this thesis, we can approximately identify ourselves as the sender, the audience as the receiver, and the chosen medium as the language.

2.1.1 Target

In science communication, the audience to which a specific communicative product is directed is often referred to as the *target*. Identifying the target is crucial and comes before the content because the complexity of the proposed content depends on the target. When designing communication, profiling the target is always critical to understand their needs and inclinations: this allows for the selection of appropriate content, language, and approach. Although this profiling often takes place through categorizations based on a series of parameters such as age, social context, and education level, today, there is much focus on the nuances that different individuals within general categories may possess.

For the VR product developed during this project, two audience levels were identified. At the first level, we have an audience of young adults, including both secondary school and university students and workers, around 20 years of age. Generally, this segment of the population is highly attracted to new technologies and particularly fascinated by immersive experiences. The sense of wonder and detachment from reality generated by a virtual experience can resonate strongly with young people, and their familiarity with technology makes them less susceptible to the disorientation and difficulties older individuals may experience during VR experiences. However, we also have a secondary target consisting of a general audience. The expression "general audience" is often frowned upon by science communication specialists because targeting a general audience implies a lack of focus on a specific target, compromising the effectiveness of communication in terms of accessibility. However, in this context, "general audience" is referred to as a secondary target, meaning that the virtual experience has also been designed and developed with the awareness that people outside the primary target may also use it. Ensuring the experience is accessible, comfortable, and welcoming represents an achievement of a successful user experience in general terms.

2.1.2 Medium

Once the final target audience has been identified, it is good practice in science communication to analyze which media may offer the best opportunities to address that target. The plural is necessary, as one should not limit themselves to a single medium but explore multimedia and cross-media options to structure a multi-faceted communication. A multimedia product is not necessarily more effective: a well-designed activity can be highly successful even if it uses simple tools and a direct and focused language. At the framework level, it is important to consider the role of art: artistic representations can transcend the didactic dimension that often envelops science communication and reach the audience through emotional resonance.

In this project, different types of media were explored, although all belonging to the extended reality sector. As we will see in Chapter 4, virtual reality was chosen for its potential in terms of immersion and interaction.

2.1.3 Content

Regarding the content, one must ensure that the appropriate level of complexity is chosen, always proportional to the interlocutor's capacity for understanding. Moreover, one must accept that not all information can be communicated in the same way or with the same level of depth. Thus, when we talk about content, we are not only referring to scientific concepts but also to how these concepts are presented. Attention must be paid to storytelling and entertainment, balancing this aspect with the scientific one. We will dedicate Section 2.3.2 to the role of storytelling in science communication and, in particular, in the product developed for this project.

Communicating means informing, engaging, interesting, involving, influencing, and explaining simultaneously: if one demands the attention and effort of the interlocutor, one must also engage them emotionally. When engagement breaks through the barrier of unilateral communication, the audience becomes an active participant and can relate to the content in a much more meaningful way. The virtual experience developed during this project exploits the interaction capabilities of the medium and gamification dynamics (described in Section 2.3.1) to enhance the impact of the content.

As for the individual scientific concepts included in the virtual experience, the next chapter will provide an overview of the latest information regarding lunar exploration, while the devices used to translate this content into the virtual world will be described in Chapter 5.

2.2 Scientific Communication model evolution

Communication has made a disruptive entry into the contemporary scientific landscape, carving out an increasingly prominent space. However, the idea of a cross-sectional dissemination of knowledge, not limited to academia but aimed at society as a whole, has roots dating back to antiquity. *De rerum natura* (Carus et al., 2003) by Lucretius can be considered one of the first works of scientific dissemination in history. In the Latin poet's work, which expounds the precepts of Epicurean philosophy, we already find many aspects that today are crucial themes in science communication. In particular, the choice to use an artistic voice to convey concepts finds its legacy in the modern blend of science and the arts, as well as in the innovative educational approach known as *STEAM* (*Science, Technology, Engineering, Arts, Mathematics*, Khine and Areepattamannil (2019)). In the meantime, the role of science, and consequently that of scientific communication, has changed significantly. In this section, we will explore the historical trajectory of scientific communication.

2.2.1 From the classical to the modern age

In antiquity, it was common for knowledge to be held by a very narrow elite and to be jealously guarded. In classical Greece, with the birth of philosophy and the first schools of thought, knowledge for the first time began to have a public connotation. However, the possibility of pursuing studies was typically reserved for the few, so the spread of knowledge remained confined to a limited portion of society: the Academy. Nevertheless, the Greek world made a crucial contribution to the future of communication in terms of culture, introducing new forms of expression such as theater and codifying the practices of exposition and narration. The Roman world followed a similar trajectory, but in Rome, the development of a ruling class that assimilated Greek culture enriched the pool of interest in new artistic content, including *De rerum natura*. The late Roman Empire and the early Middle Ages saw a significant cultural decline, while in the East, a great contribution to scientific progress came from the Arab world. Although in this case, it cannot be strictly defined as scientific communication, the contacts and trade exchanges between peoples allowed Arab discoveries and innovations to circulate throughout the Mediterranean basin. Even today, we can trace the Arab heritage in the etymology of certain scientific terms (*algorithm*, *algebra*) or astronomical names (*Altair*, *Aldebaran*, *Algol*, *Algieba*). With Humanism and the Renaissance, a renewed interest in the natural world emerged in the Western landscape. This set in motion the process that would lead to the scientific revolution and the Enlightenment. The newly-born science remained largely confined within the academic realm, but the power of the printing press and the rise in literacy levels facilitated the birth of a new audience, ready to embrace some important exceptions, such as Galileo's *Dialogo Sopra i Due Massimi Sistemi del Mondo* (Galilei, 1632) and Voltaire's essay *Éléments de la philosophie de Newton mis à la portée de tout le monde* (Voltaire, 1738). In these works, the authors aimed to present the scientific theories of reference - Copernican for Galileo, Newtonian for Voltaire - using accessible language and an engaging style. However, it was only with the Industrial Revolution, the age of inventions, and the rise of the middle class following the French Revolution that interest in science began to spread on a large scale. Scientific institutions began to take on a central role in technological development, and what was once called natural philosophy gave way to the science-technology pairing we still have today. In this context, world exhibitions, scientific journalism, and sector journals emerged. The paradigm of this new large-scale scientific communication remained unchanged even with the advent, in the 20th century, of new technologies and communication media.

2.2.2 Information deficit model

The paradigm established in the 19th century and which remained predominant for a long time in the field of scientific communication is the so-called *Information deficit model*. This model views people outside the academic community as empty vessels, ready to be filled with information provided by scientists. This approach presupposes, on the one hand, the absence of preconceived notions in people's minds about scientific topics and, on the other, a positive disposition to receive the content proposed by scientists with genuine interest and unquestioned trust. Such assumptions led to a one-way, top-down communication approach focused solely on content transfer.

The model remained largely faithful to itself, gradually adapting its language in relation to the target audience. The advent of mass media made scientific content more accessible, and new forms of communication were successfully experimented with and implemented: consider popular science magazines, documentaries, and science TV shows. The media increased public interest in science and fostered the growth of basic scientific literacy through new communication techniques, such as visual suggestion and storytelling. However, the fundamental approach remained the same.

Over time, several critical issues emerged in this model. Genuine public interest cannot be taken for granted, especially in a context full of stimuli and information, as delineated by the digital revolution. In the contemporary landscape, public attention is constantly contended for, and expecting the public to be inherently interested in the proposed content is already a flawed starting point. Moreover, in today's world, it is relatively easy for the public to build an understanding of scientific topics, even just by interpolating information from various contexts and languages: everyone has heard of black holes, and probably every person has a different idea in their mind when they think of a black hole. Thus, the assumption that people are empty vessels to be filled with information clashes with a very different reality, in which preconceptions and (unintentional) misinformation are widespread. Finally, public trust in the proposed content is not always as positive as the model assumes. Events in recent years are illuminating in this regard: contemporary scientific issues like climate change have received mixed feedback from the public. Similarly, the COVID-19 pandemic has shown how even in health matters, the public exhibits some reluctance to trust scientists. Clearly, these topics have a significant impact on people's daily lives, choices, and actions, representing fertile ground for resistance and hostility where scientific content endorses certain choices over others. Such broad issues have economic and social implications, and the involvement of large-scale interests significantly complicates the communication between the scientific community and the individual. Conflicting information from different sources, all claiming comparable validity, disorients individuals and undermines their trust in science. Focusing communication solely on content transfer overlooks the aspects of methods and policies that characterize modern science, depriving the public of essential tools for navigating a complex and varied landscape.

In this context, the arrival of social media has had an ambivalent impact: on the one hand, the presence of institutions and science communicators on social media gives the scientific community a new voice to speak to the public. On the other hand, the nature of these communication tools facilitates the spread of misinformation. The circulation of inaccurate, partial, or entirely false information, such as fake news, is facilitated by the ease and speed of content sharing. The structure of algorithms that underpins the suggestion of social media content generates *echo chambers*, a phenomenon where certain groups of users interact exclusively with content aligned with a particular line of thought. This is a general problem of communication on social media, which tends to exacerbate ideological polarization rather than foster constructive dialogue. In the realm of scientific communication, the result is the formation of factions that interact negatively with scientific information.

2.2.3 Dialogue Model

The critical issues that have emerged in recent decades have led to a paradigm shift. The *dialogue model* that has become more and more prominent in recent years better meets the needs of a complex society characterized by extremely rapid evolution, ever-new and diverse stimuli, and extended and stratified interactions among individuals. This model entails a bidirectional communication, expressed on various levels and through different modalities, between the scientific community and the social fabric, as depicted in figure 2.1. The model envisions a science that questions itself in relation to external inputs, not so much regarding the results it achieves, but more concerning the common goals to be reached, modes of collaboration, and innovations in terms of policy. In this sense, the dialogue more closely mirrors the concept of communication in its original connotations, as discussed at the beginning of this chapter. This new model is also referred to as the *public engagement* model, an expression that is gaining traction even outside the realm of scientific communication, and which we will analyze in the next section.

In light of this paradigm shift, it is also important to note how the objectives of scientific communication have changed: whereas content once held an irreplaceable centrality, today communication also focuses on promoting scientific culture in a broader sense and seeks to use science as a substrate in which to plant the seeds of a new collective well-being (Bowler, 2016). In this regard, the world of science communication has begun to explore new paths to meet these new goals: in the field of astronomy, but not only, there are projects that promote collaboration between different people and communities (Guinan and Kolenberg, 2015), projects related to inclusion, and projects simply aimed at providing enjoyable experiences that can foster a positive and open attitude towards

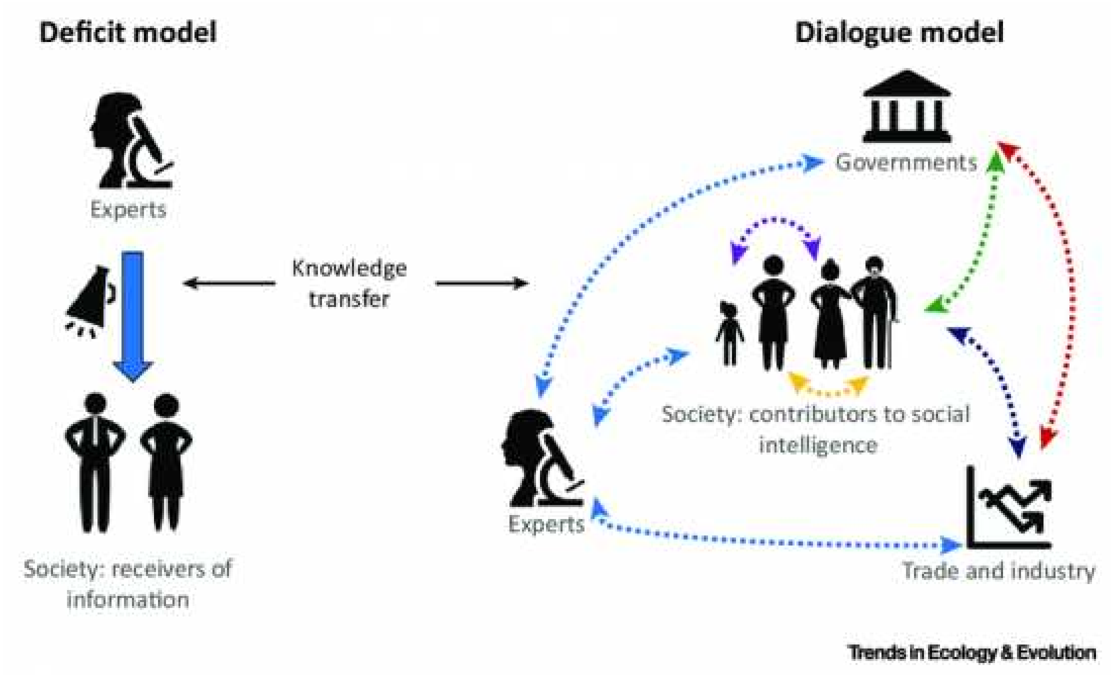


Figure 2.1: Diagram showing the different approaches for information deficit and dialogue model.

science in the public. This broader perspective also underpins new proposals in terms of public engagement activities. New ideas continue to emerge, new media and new approaches are studied, explored, and tested in public engagement contexts that are becoming increasingly frequent: from hands-on activities to focus groups, from citizen science campaigns to science shows, from artistic performances to virtual tours.

2.3 New paradigm: public engagement

As the name suggests, public engagement refers to the direct involvement of the public in an activity. The concept can have political or corporate connotations, but it is also gaining traction in the field of scientific communication, particularly within the dialogue model. Public participation in scientific research can occur at different levels, depending on the type of audience and the specific activity. Figure 2.2 comprehensively shows the different levels of engagement, highlighting how the objectives change based on the level of active public participation. If at the innermost level we have partnerships and shared decision making, characterized by a high level of active participation, at the other end we find the classic, unidirectional media, such as newspapers, websites, and TV programs, which aim to inform or inspire individuals and the community. It is important, therefore, to emphasize that information - understood as content transfer - does not disappear entirely from the model but is instead placed within a broader and more complex framework. Mutual listening and collaboration between scientists and the public are at the core of this approach, regardless of the level of engagement. Within this model, a communication product takes on plural connotations in its various aspects. Concepts like sender and receiver become much more nuanced, as dialogue also manifests as a role exchange between the different actors involved. In this sense, the creative process of a public engagement product is just as important as the final product. During the design and development of a project, discussions, exchanges, and collaborations occur at various levels among the different actors in the process. Thus, beyond the final target to which the developed product is directed, there are a series of intermediate targets, identified by all the people who have participated or collaborated in some way in the development process. Public engagement is oriented toward ensuring the involvement and personal growth of all the actors at all levels.

The product developed during this research project fits into the context of public engagement from different angles. On one hand, the extended reality experience is based on scientific contents and aims to transmit them to the user. By transmitting content related to the future of lunar exploration, rather than archived scientific results, the experience is also positioned as a product with inspirational purposes. The use of immersive and interactive technology, such as virtual reality, is expected to result in a high level of engagement in the strict sense: the public should feel particularly involved in an experience like this compared to activities that are equally informative but much less functional in terms of active participation and visual representation. The "wow effect" guaranteed by the power of immersion and the experiential nature of an interactive VR product serves as an emotional glue that helps maintaining high user engagement. In the following subsections, we will explore some aspects generally very important in the field of public engagement and that also represent central characteristics of the product developed during this research project: playing and storytelling.

Based on these considerations, if we were to place the product on the graph shown in Figure 2.2, we should position it in the second ring from the right. However, there is another aspect to consider. The realization and testing of the

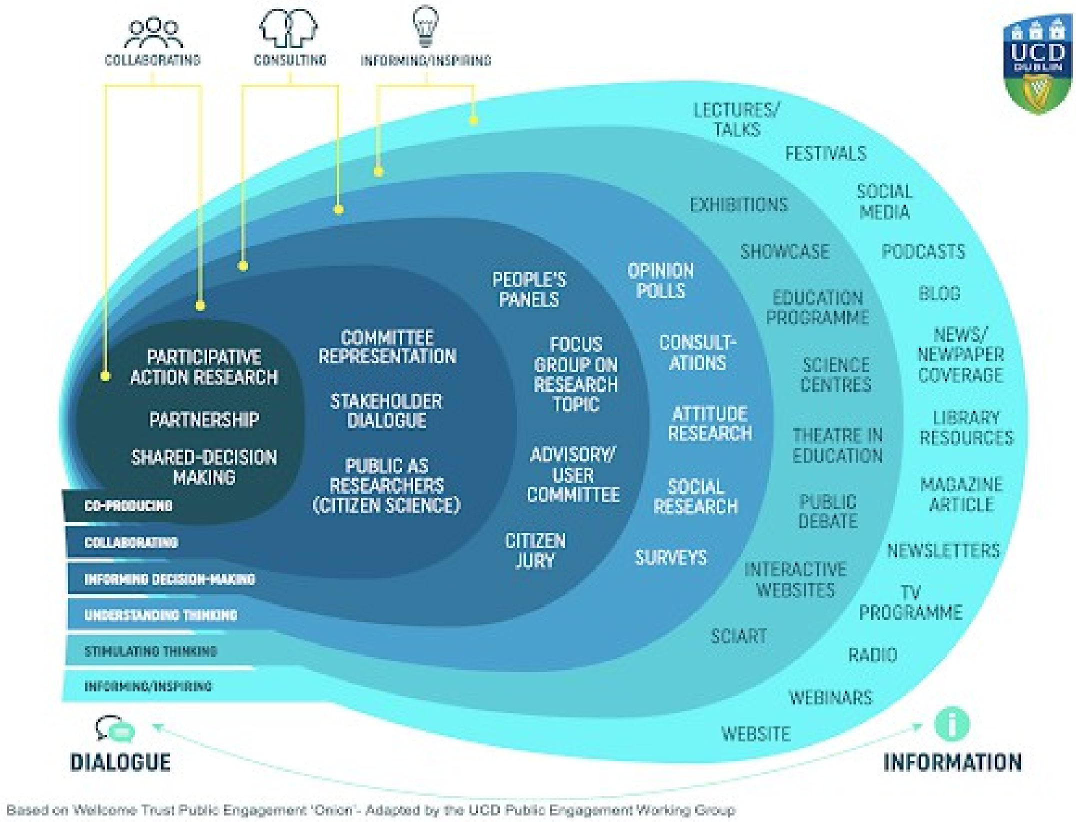


Figure 2.2: Public Engagement onion diagram, representing in concentric layers the different types of activities under public engagement. Adapted from University College Dublin.

VR product required the support and collaboration of various professionals outside the scientific community. Consultations with communication professionals and multimedia product creators were fundamental to implement a successful design. Preliminary trials and beta testing were conducted during the development phase, involving individuals from various sectors. Furthermore, for public testing, the hospitality and support of a science visitor center - the SPARKme in Matera - was crucial, contributing to strengthening the collaboration between the center and the National Institute of Astrophysics (INAF). In this sense, a public engagement operation developed around the product, which enhanced relationships with different actors in the public landscape, in the spirit of the synergy aimed at collective well-being that underlies this new plural model of communication.

2.3.1 The role of playing

In this section, we briefly discuss one of the oldest means of communication in human history: playing. Although playing has been part of human history since prehistoric times, a precise and systematic reflection on this theme has developed only in the last century. In ancient Greece, Plato (Ferrari and Poli, 2005), Aristotle (Laurenti, 2019), and Plutarch (Voinič, 2012) spoke of playing as a pedagogical tool: the similarity between the words $\pi\alpha\iota\delta\iota\alpha$ (paidia), referring to playing, and $\pi\alpha\iota\delta\epsilon\iota\alpha$ (paideia), referring to education, denotes the indissoluble link that has been recognized between these two aspects of human development since ancient times. Another example comes from the Roman world, with Quintilian (Pennacini, 2001) assigning an important role to play in student training. *Ludus litterarius* was the name given to the first stage of a scholar's education in Rome, but the word *ludus* also had connotations related to physical exercise and gladiatorial games, and its root is still found in the etymology of many words associated with play today. These linguistic associations were lost when Caillois (Caillois, Rovatti, and Dossena, 2014) explored people's disposition toward playing, identifying *paidia* as the carefree and unregulated approach often seen in children's activities, and *ludus* as the rigid and methodical approach that characterizes strategic games. In the last century, however, reflection on playing has made great strides, and it has gained an even more relevant role. In his anthropological essay *Homo Ludens* (Huizinga and Van Schendel, 2002), Huizinga identifies play as something "indispensable to the individual [...] and society

[...]." He begins to recognize the biological function of playing, then attributes it an expressive value and potential for creating social bonds. For the first time in history, a deep epistemic similarity between playing and ritual was identified. In this context, it becomes clear that playing fits perfectly into the multi-layered and nuanced communication model envisioned by public engagement. Today, the topic of playing as a medium for communicating and transferring content, interpretations, and meanings is once again central to the cultural debate. Playing allows the user to be an active participant in a discovery or learning process by pursuing goals that feel close, concrete, and desirable, making the user emotionally involved (Anolli and Mantovani, 2012). Gamification, the approach that aims to insert game mechanics into various activities to enhance their impact, has seen transversal growth over the last 15 years. The field of scientific communication is not exempt from this, and many public engagement activities now implement gamification mechanics: escape rooms (Vörös and Sárközi, 2017), interactive mazes (Sandri et al., 2023), and board games (Ricciardi et al., 2023) are finding new applications in this field, in ways that were hard to imagine just a few decades ago.

In the context of this research, the use of a medium like VR has proven particularly suitable for implementing gamification schemes and methods, even though the final product cannot be considered a game in the strict sense. According to modern definitions, playing takes place in a specific space, on a different level of reality (Fink and Masullo, 1969), in a parallel world where the rules of everyday life do not apply but only those of the game itself: Huizinga, almost to underline once again the parallel between playing and ritual, calls this space the "magic circle." This term, still used in the terminology of Game Studies today, identifies the playing space (Bertolo and Mariani, 2014), not only as the physical location where it takes place but also as the conceptual framework within which all the elements of the game find their place. These considerations show how a virtual experience lends itself particularly well to being designed according to a game-like dynamic. The transition to another level of reality, intrinsic to any playing activity, is explicitly and consciously carried out within a virtual experience. For this reason, implementing gamification dynamics within the experience and proceeding with development by considering game design techniques treated in modern Game Studies seemed like a natural and profitable choice.

2.3.2 The role of storytelling

Storytelling has always played a crucial role in human development. Stories are an ancient medium for conveying content of all kinds. The transmission of teachings to younger generations, the planning of complex activities, the sharing of new discoveries - territorial, technological, spiritual - and many other aspects of our ancestors' lives passed through the filter of narration. Emerging after the development of articulate language and symbolic intelligence, storytelling contributed to the development of new capabilities for our species, enabling members of human communities to share individual perceptions and face challenges with a completely new approach. With the power of storytelling, humans managed to go beyond direct experience of the world, opening themselves to a plural, collective, social experience. Sociality itself acquires, thanks to storytelling, a completely new dimension.

Storytelling played an important role in scientific communication even within the information deficit model. Some illustrious scientists of the last century demonstrated great ability in conveying even complex concepts to the public through speeches characterized by appropriate language, clear exposition, and captivating storytelling as a rhetorical technique. In the field of physics and astrophysics, names like Richard Feynman and Carl Sagan stand out internationally. There are also cases where storytelling - in the strict sense - has supported scientific communication through artistic works inspired by scientific themes. Although the authors' goal was not to communicate scientific concepts but to use such themes to provide a context for the narrative, it is undeniable that some scientifically inspired stories have had, and continue to have, an inspirational value for the public (Laprise and Winrich, 2010). Think of the impact that science fiction authors like Isaac Asimov and Arthur Clarke had in fostering interest in the world of science. An entirely Italian example is *Cosmicomiche* (Calvino and Milanini, 1997), where some scientific concepts serve as the starting point for the narrative (Sandrelli, 2023).

Today, the role of storytelling is even more central because, within public engagement, the goal is to establish a connection between the scientific community and the public (Joubert, Davis, and Metcalfe, 2019), and the emotional impact of storytelling provides fertile ground for this (Davies et al., 2019). In a communication model that envisions public participation, and therefore the development of diversified activities with various levels of involvement, stories are not just a finished medium for trying to transfer content; rather, storytelling cuts across activities and holds an important role within them.

In the context of this research, storytelling has played an important role during the development of the VR product. Although narrative was not the medium that is used in this kind of activity it constituted a general framework for the development process. The narrative has often served as a glue between the various aspects of the experience: scientific content, mechanics, and interactions. Furthermore, the immersion that a virtual experience inherently provides is further enhanced by a narrative that put the user as the protagonist. The user becomes a character in a new environment, living in specific places and interacting with specific objects in the flow of the story. The narrative is supported by the strong visual impact provided by virtual immersion, and this combination of elements is expected to make the experience particularly effective for young people (Finkler and León, 2019).

3

The scientific context: Moon exploration

One of the initial steps of this work involved finding a suitable theme on which to base the development of the product. As we will see in Section 2.3.2, this is crucial to build a coherent and engaging storytelling. The idea of leveraging extended reality technologies opens up a wide range of diverse possibilities: narrowing the product to a single area of scientific research was necessary from the outset to channel the work in a well-defined direction.

The exploration of the Moon is an astronomical topic that is appealing for innovative research in the communication field. In the history of space explorations, the Moon was the goal that captured and focused the attention of the public much more than anyone else: the legacy of the Apollo program is not confined to the scientific context but it must be considered as a point of reference also under a communicative and cultural profile. The Artemis program is expected to follow the same path in the next years and resources that public and private agencies are spending on space missions suggest that we find ourselves at the dawn of a new space race that will have the Moon as the first goal. Section 3.1 is dedicated to the description of this aspect.

From a scientific point of view, the Moon will be a site of interest for many fields of research. The characterization of the lunar geology can give information about the evolution of the Solar System. In this context, a lot of in-situ missions have been proposed for the nearby future, in order to study the lunar underground by spectroscopy, radar, imaging, chemical analysis and seismic analysis.

Section 3.2 is dedicated to a brief presentation about these themes.

Also, the Moon is expected to provide new opportunities for lunar-based astronomical observations. The absence of an atmosphere and the long duration of dark sky conditions would guarantee significant observational advantages. Section 3.3 reports some details in this sense.

Finally, the exploration of our satellite brings hard challenges from a technological point of view: telecommunications, astronauts' support and protection from radiation, in-situ resources utilization (ISRU), and realization of a permanent sustainable basecamp. New research is needed in this direction, which will also have possible implications for our life on Earth. This aspect is presented in Section 3.4.

Some of the aspects discussed in this chapter have inspired the content featured in the virtual reality experience and described in Chapter 5. In particular, in Section 5.3, we will provide more detailed information on which scientific aspects were included in the virtual experience and how they were presented.

3.1 A new space race

In the 1960s, the Apollo program captivated audiences around the world. The complexity of the challenge, combined with the tight deadlines, excited the public to such an extent that the narrative of one of humanity's greatest achievements continues to hold a near-intact allure. Public interest began to wane in the 1970s after the symbolic objective had been reached, with attention shifting elsewhere despite the significant scientific achievements of the later missions. Today, the Artemis program carries the legacy of Apollo both scientifically and culturally (Pernet-Fisher et al., 2019).

3.1.1 Artemis

The short-term goal of the Artemis program is to return humans to the Moon, while its long-term objectives include establishing a continuous and self-sufficient human presence, taking the first steps toward developing a lunar economy, and laying the groundwork for future human exploration of Mars (NASA, 2020). Figure 3.1 and Figure 3.2 illustrates the different phases of the program as currently planned:

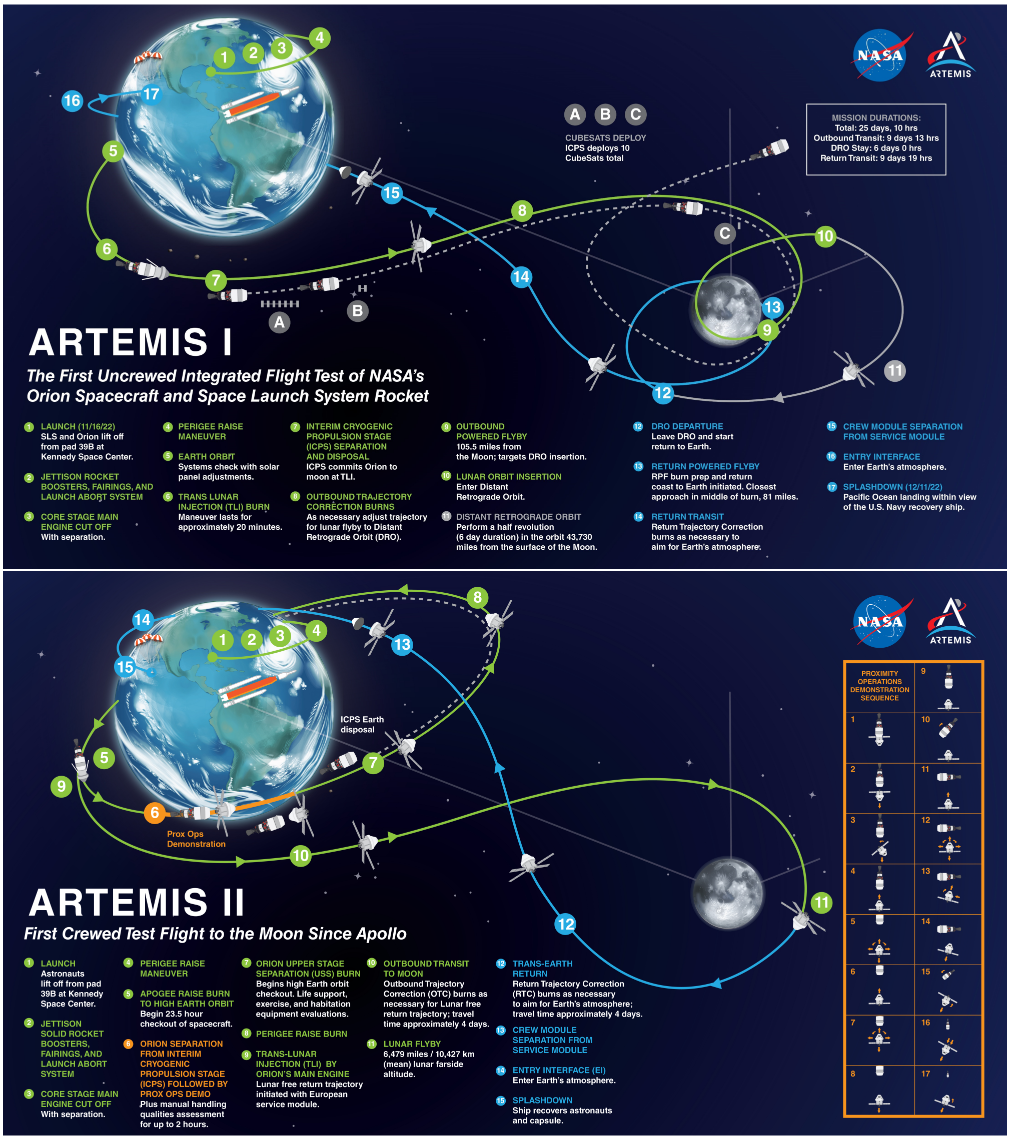


Figure 3.1: Overview of Artemis I and Artemis II missions. Credits: NASA

- Artemis I: uncrewed flight test of the Space Launch System and the Orion spacecraft around the Moon.
- Artemis II: first crewed flight test of the Space Launch System and the Orion spacecraft around the Moon.
- Artemis III: first human exploration of the region near the lunar South Pole.
- Artemis IV: debut of humanity's first lunar space station, a larger, more powerful version of the SLS rocket, and a new mobile launcher.

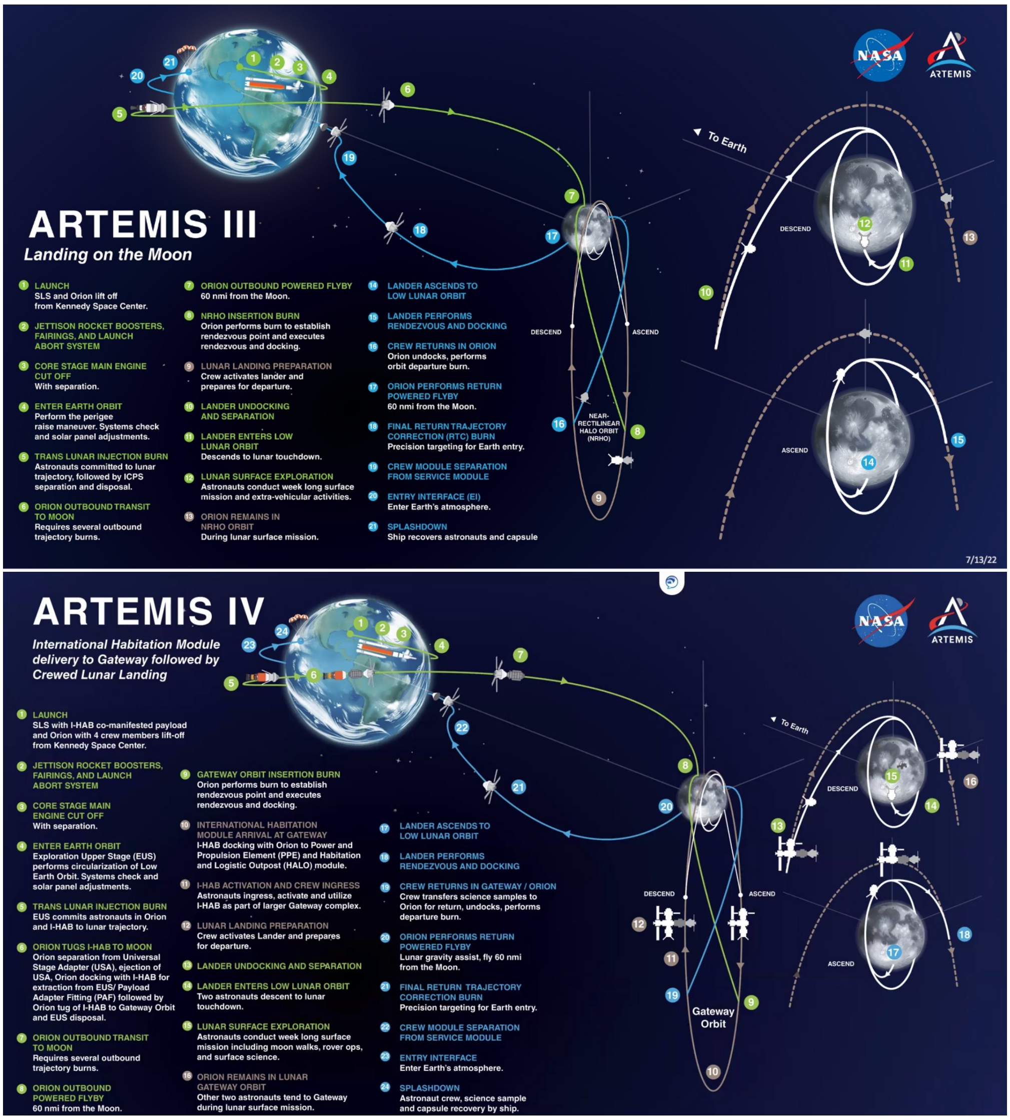


Figure 3.2: Overview of Artemis III and Artemis IV missions. Credits: NASA

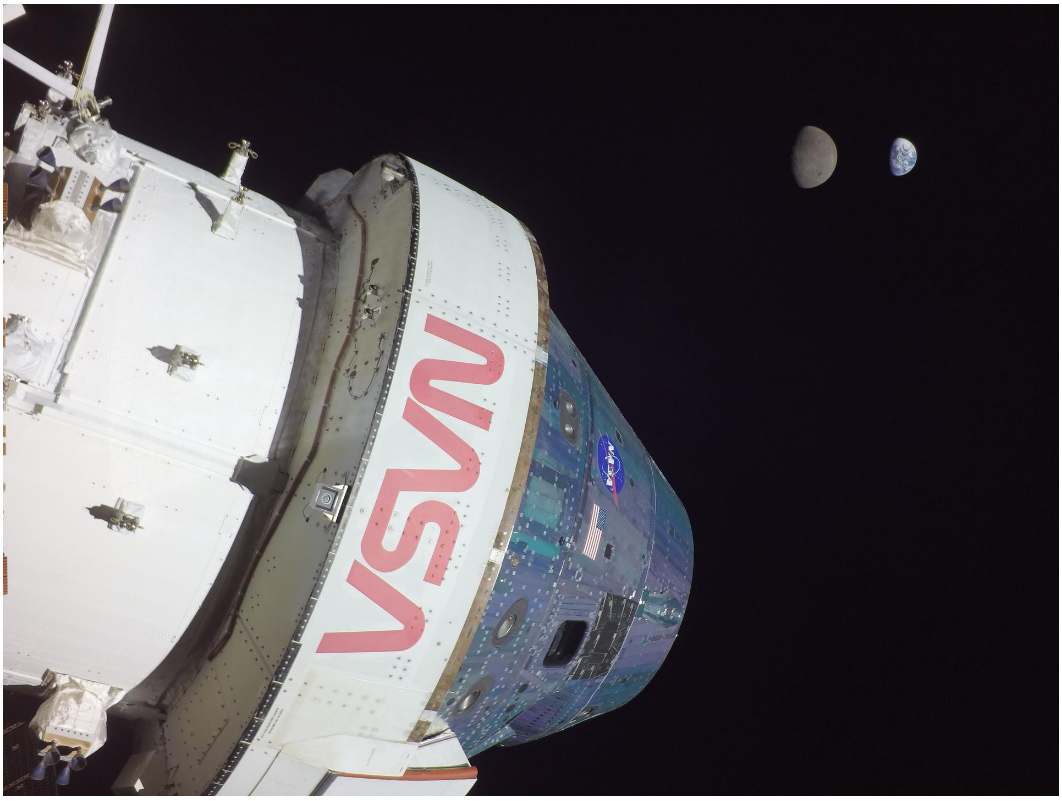


Figure 3.3: Orion with Earth and the Moon in background. Artemis I flight-day 13. Credits: NASA

The Space Launch System (SLS) was developed specifically to launch super-heavy rockets necessary for crewed missions to lunar orbit. Similarly, the Orion Multi-Purpose Crew Vehicle (MPCV) was designed to house the crew and service modules, following the design principles used for the command and service modules of the Apollo program. The Lunar Gateway, introduced in Artemis IV, will play an important role as a lunar orbiting space station, providing support for surface exploration missions and serving as a base for future Mars missions (Fuller et al., 2022).

Artemis I launched on November 16, 2022, and returned 25 days later (Figure 3.3). Its goal was to test the reliability of the SLS and Orion systems, including the service module, in preparation for a crewed flight, and to validate the spacecraft's heat shield for high-speed re-entry. The success of the mission bodes well for the subsequent phases of the program.

3.1.2 International Collaboration

The Artemis program is led by NASA (National Aeronautics and Space Administration) in collaboration with several space agencies: ESA (European Space Agency), JAXA (Japan Aerospace Exploration Agency), and CSA (Canadian Space Agency). This collaboration highlights how space exploration requires joint efforts, shared goals, and the pooling of expertise, reflecting the sense of unity that the Apollo program and the space era have left as a legacy.

Italy has shown great interest in Moon exploration: it is one of the six themes of national interest outlined in the PNR 2021-2027, under the section "Exploration and observation of the Universe." The National Institute for Astrophysics (INAF) leads a national coordination effort to define an Italian roadmap for Moon exploration (*Piano Triennale INAF 2021-2023* 2021). Furthermore, the bilateral agreement signed in 2020 between NASA and the Italian Space Agency (ASI) within the Artemis program demonstrates how lunar exploration has become a central theme in politics and international relations.

3.1.3 Commercial Aspects

Unlike the Apollo program, where all aspects were managed internally by NASA, today's lunar exploration sees private companies playing a crucial role in the development and implementation of key components. The collaboration between space agencies and private enterprises has significantly intensified, and the international scope of this new era of space exploration has sparked economic interests worldwide. Numerous companies are increasingly involved in this *new space race*, particularly with the commercial opportunities offered by the emerging space economy.

SpaceX has become a leader in space technology, particularly with its Starship vehicle, which NASA has selected to land astronauts on the Moon as part of the Artemis program. *Blue Origin* is developing its Blue Moon lander, contributing to NASA's Human Landing System (HLS) initiative, aimed at facilitating lunar exploration. Astrobotic and Intuitive Machines are spearheading commercial lunar lander programs through NASA's Commercial Lunar Payload Services (CLPS) to deliver scientific and technological payloads to the Moon. Thales Alenia Space is conducting feasibility studies for lunar modules and systems in support of a sustainable lunar exploration program, with the goal of establishing a permanent base for long-term missions. The initial missions will last two weeks, gradually extending in duration, with fully operational systems expected by 2030.

Private companies are involved in many projects related to the development of new technologies for future lunar exploration, as discussed in 3.4. A growing number of commercial entities view the Moon as the next frontier for economic activity. The lunar economy is seen as a long-term driver for innovation and profit, with lunar exploration acting as a stepping stone to deeper space ventures and a foundation for an intensive space economy.

3.2 Science on the Moon

The upcoming lunar exploration will provide the opportunity to study our satellite much more closely. With future lunar missions new opportunities will arise for conducting advanced scientific experiments. The following subsections outline the main areas of research that will be central to scientific investigations on the Moon, including studies on geology, seismology, and phenomena related to lunar dust.

3.2.1 Lunar Geology

The Moon Mineralogy Mapper (M^3), on board the indian space mission Chandrayaan 1, provided the first mineralogical map of the lunar surface. The instrument detected spectral signatures of water-bearing materials in the polar regions (Pieters et al., 2009). In 2009, thanks to the NASA Lunar Crater Observation and Sensing Satellite (LCROSS), the first direct measure of the presence of water in lunar subsoil was performed (Colaprete et al., 2010). Following in situ analysis provided encouraging results, as the Chang'e-3 Visible and Near-infrared Imaging Spectrometer (VNIS) detected evidence of high-Ca pyroxene and olivine at its landing site (B. Liu et al., 2014). New instruments have been proposed to improve the analysis of lunar mineralogy during future in-situ missions.

PROSPECT is an ESA instrument designed to study the lunar subsurface down to a depth of 1 meter, particularly analyzing the presence of volatile elements in the regolith. The instrument mainly consists of two systems: the drilling module, called ProSEED, and the ProSPA system, a laboratory for isotopic analysis of ice, capable of processing and analyzing samples using two types of spectrometers (Trautner et al., 2024). ProSEED also integrates an optical imager, while ProSPA will be equipped with a sample camera capable of producing multispectral 3D images (Heather et al., 2022). Thanks to the images provided by the cameras and the analyses performed by ProSPA, the instrument will allow the characterization of the subsurface morphology and mineralogy, providing insights into the presence of volatile elements and the potential for oxygen extraction, which is crucial for future human missions (Heather et al., 2022). PROSPECT will be included in the lunar lander of the private company Intuitive Machine selected within NASA's CLPS program (Trautner et al., 2024).

3.2.2 Lunar Dust

The lunar environment is characterized by the presence of levitating dust grains. The presence of dust and its effects were already observed during the Apollo missions. Micrometeorite impacts are one of the main causes of dust lifting above the regolith surface, although UV bombardment and the solar wind have also been proposed as triggers for the lifting of charged dust grains (X. Wang et al., 2016). When the dust grains are very small on the order of nanometers and micrometers, they may assume an electric charge and the electrostatic force is responsible for their levitation: the electric charge they accumulate interacts with the electric field generated by the solar wind and the magnetosphere of the Earth. The balance of forces allows the grains to overcome the gravitational pull of the Moon and remain in a levitating state above the surface.

Characterizing this phenomenon will be crucial for human exploration, as dust grains can pose a threat to both instrumentation and astronauts' health. This is one of the reasons why several experiments aimed at analyzing floating dust have been proposed in recent years. The Electrostatic Lunar Dust Analyzer (ELDA) is an instrument proposed by Duncan et al. (2011) to study dust grains by exploiting their electric charge. Thanks to an array of wire electrodes combined with an electrostatic deflection field, the instrument will measure the mass, charge, and velocity vector of individual dust grains. ELDA is expected to measure speeds in the range of 1-100 m/s for particles within an approximate mass range of $10^{-16} - 10^{-11}$ kg.

Longobardo et al. (2013) have proposed a micro-thermogravimeter to measure the content of volatile elements and the electric charge of lunar dust: MOVIDA (MOon Volatile Investigator and Dust Analyser). MOVIDA is based on an array of micro-oscillators, with piezoelectric crystal microbalances (PCM) constituting the detecting part. A conductive electrode acts as a collector of dust particles on a micron and sub-micron scale. PCM temperature can be increased to allow the evaporation of the volatile components from a sample, thus inferring the abundance and composition of the volatile compounds. Moreover, MOVIDA will feature new-generation microbalances using an instrument-generated electric field to attract dust grains, allowing for an electrical charge characterization of levitating dust.

3.2.3 Lunar Seismology

Seismological studies in the lunar environment were conducted during the Apollo program, where astronauts deployed seismic experiments on the nearside of the Moon between 1969 and 1972 (Nunn et al., 2022). The study of lunar seismology was interrupted in 1977, with the switch-off of the Passive Seismic Experiment (Weber et al., 2022). In the context of the Artemis program, NASA will reopen our view of the interior of the Moon and new seismic studies will be performed using instruments like the Farside Seismic Suite (FSS). FSS, expected to fly to the Moon under the Payloads and Research Investigations on the Surface of the Moon (PRISM) program (launch scheduled for 2025), will provide the first seismic signals from the far side of our satellite (Panning et al., 2023). Seismic data will help investigate lunar structure, particularly the differences between nearside and farside activity.

Lunar seismology studies could have implications beyond the characterization of our satellite. It is thought that the seismic background may provide clues to constrain the stochastic gravitational wave (GW) background (Yan et al., 2024). Additionally, a Moon-based gravitational wave detection experiment would benefit from the extremely low level of seismic disturbances on the Moon (Branchesi et al., 2023). Several experiments in this direction have been proposed in recent years. The Gravitational-wave Lunar Observatory for Cosmology (GLOC) is based on laser interferometer technologies, probing GW frequencies in the range $0.1 - 5$ Hz (Jani and Loeb, 2020). The Lunar Gravitational Wave Antenna (LGWA), whose basic concept consists of an array of high-end seismometers to monitor the normal modes of the Moon in the frequency band 1 mHz – 1 Hz excited by GWs (Harms et al., 2021), could operate as an important partner for the future operations of the laser-interferometric detector LISA, as well as working autonomously on a different scientific case.

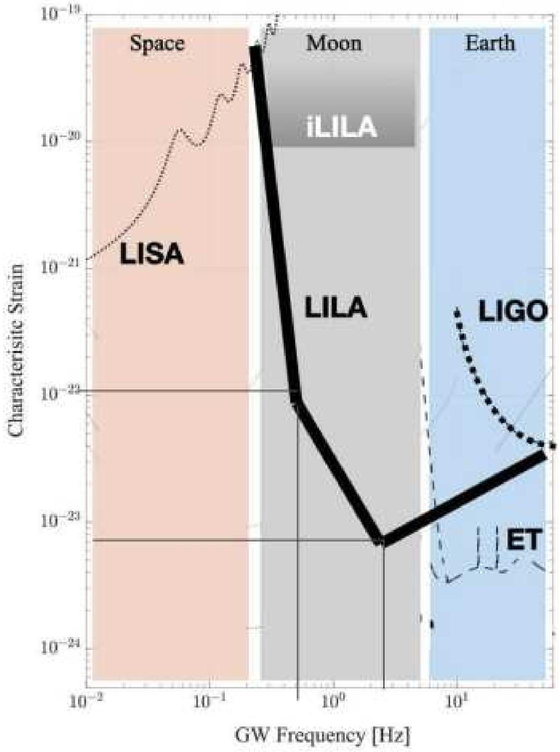


Figure 3.4: Gravitational wave spectrum covered by different experiments. Credits: LILA project group.

In this framework, a collaboration of scientists and space industries recently proposed a project for the development of another laser interferometric gravitational-wave observatory on the surface of the Moon. The project, called the Laser Interferometer Lunar Antenna (LILA), represents a new frontier for multi-messenger astrophysics (Jani, 2024). The characteristics of the lunar environment will grant access to a new window in the gravitational-wave spectrum, not yet covered by Earth or space technologies (Figure 3.4). The absence of an atmosphere implies no need for vacuum maintenance over kilometric arms, though the resulting thermal variations could affect measurements with significant fluctuations in thermal noise and temperature-dependent noise.

Other lunar seismology studies that could be conducted in the future are related to the detection of signals from Strange Quark Matter (SQM) (Herrin, Rosenbaum, and Teplitz, 2007). Witten (1984) proposed the idea that matter composed of up, down, and strange quarks could be stable at low energy scales. Potential structures composed of this matter would generate, upon impact with the lunar surface, a seismic signal different from that generally associated with common meteoroid impacts or lunar quakes. Although this signal could also be detected on Earth, estimates by Banerdt et al. (2006) suggest a significant advantage in detection in the lunar environment.

3.3 Science from the Moon

The wide-reaching implications of the seismological investigations that can be conducted on the lunar surface connect directly to the theme of the Moon as a laboratory or as a privileged observation site. The lunar environment offers conditions similar to those of interplanetary space, making it a suitable location for experiments that aim to study these characteristics. One promising area of research is astrobiology. Additionally, certain characteristics of the Moon, particularly its far side, make it an ideal location for hosting observational instruments in various fields of space sciences.

3.3.1 Astrobiology

Astrobiology experiments in space are often passive, relying on exposing organisms to the conditions of the space environment. A long-term goal is to study the origin of life by investigating how macromolecules react to an environment dominated by UV radiation and ionized particles (C. Cockell, 2010), aiming to understand which of these can serve as biomarkers. Life-in-extreme-environment experiments have already been conducted in space: the EXPOSE facility, mounted outside the ISS, allowed the exposure of various organisms to the space environment, hosting a series of experiments aimed at characterizing the evolution of organic matter in extraterrestrial environments and its potential implications in astrobiology (Bryson et al., 2011; Noblet et al., 2012; de Vera et al., 2012).

The Moon is expected to host future EXPOSE-like experiments. Proposals have been considered by ESA for the inclusion of astrobiology experiments on the European Large Logistic Lander (EL3), expected to launch in 2031. In particular, after the successful results of EXPOSE-R2, Raman and PanCam instruments could perform new analyses on the lunar surface regarding the stability of life markers in the lunar environment (de Vera et al., 2012). Among the various advantages of a lunar lander experiment is the more intense radiation environment and the possibility of prolonged exposure.

3.3.2 Moon-based observatories

The lunar environment offers significant advantages for observing the universe across a wide range of wavelengths.

The absence of an atmosphere and ionosphere makes the Moon an ideal location for telescopes operating in the near-ultraviolet (NUV) domain (200-320 nm), enabling high-performance observations of transient sources. As an example, Mathew (2018) proposed the Lunar Ultraviolet Cosmic Imager (LUCI), an NUV telescope designed to fly as a scientific payload on a lunar mission.

In the radio domain, frequencies below 30 MHz remain largely unexplored since the atmosphere of the Earth reflects radio waves at these frequencies, preventing ground-based observations. Installing radio instruments on the far side of the Moon would benefit from the absence of atmosphere, stable temperature conditions, and natural shielding from radio interference from Earth. To this end, ESA has established a thematic team to design and develop an Astronomical Lunar Observatory (ALO) as part of the EL3 program (Klein Wolt, Falcke, and Koopmans, 2024). Although this project may focus on solar and Jovian emissions, its primary objective is to detect and map the 21-cm hydrogen line emission from the early universe, with frequencies now in the $1.4 - 140$ MHz range.

The Radio Observatory on the Lunar Surface for Solar studies (ROLSS) is another proposed project, still at the conceptual stage. It envisions a low-frequency radio interferometric array placed on the lunar surface, designed to study particle acceleration processes in the Sun and the inner heliosphere. The primary goal is to observe radio emissions produced by solar bursts during coronal mass ejections, in order to identify the particle acceleration sites and the mechanisms that trigger them (Lazio et al., 2011).

Additionally, we cite also the International Lunar Observatory (ILO), a private scientific and commercial mission by the International Lunar Observatory Association (Durst, 2020). This mission aims to establish a permanent observatory near the lunar south pole, featuring an optical telescope and possibly a radio antenna.

Beyond the electromagnetic spectrum, astroparticle physics also has an interest in building a permanent cosmic-ray (CR) observatory on the surface of the Moon. Such an observatory, with its large sensitive area, could enable a rich observational program within a short time frame, probing the PeV energy range where the cosmic-ray spectral anomaly is located (Marrocchesi, 2023).

More uncommon proposals relate to observing the Earth from the Moon. Renga and Moccia (2016) propose a lunar station for microwave Earth remote sensing. The idea is to exploit the motion of the Earth-Moon system to create a synthetic aperture radar (SAR) with an exceptionally long synthetic antenna. This would enable ultra-high-resolution observations (around 1 m).

Clearly, permanent observatories are costly and technologically challenging projects that are likely to be built only in the long term. The difference between these and the in-situ scientific experiments discussed in Section 3.2 is that the latter will precede stable human settlements, whereas large-scale projects like observatories will likely be completed later on.

3.4 Human exploration

Human exploration of the Moon will involve a range of scientific and technological challenges. In the following sections, we present some of these challenges and the projects that are currently underway to address the needs they entail.

A sustainable human presence on our satellite must overcome fundamental issues, such as the availability of essential elements for life - water and oxygen - and astronaut sustenance. A sustainable settlement will need to autonomously produce these essential resources, utilizing the limited resources provided by the lunar environment; this approach is referred to as *in-situ resources utilization* (ISRU). The use of local resources is the first step in constructing facilities that can host human presence or provide necessary support for activities on the lunar surface. The construction and safety of these structures are equally crucial aspects of lunar exploration. Finally, the implementation of communication systems will need to ensure stability and efficiency in the transmission of information between the Earth and the Moon, as well as within the lunar environment itself.

3.4.1 ISRU

The lunar environment presents several characteristics that make it particularly hostile and the absence of fundamental elements to sustain human life is undoubtedly one of the problems receiving significant attention today. Given the logistical impossibility of continuously transporting useful resources from

Earth, the importance of ISRU is widely recognized in future lunar exploration projects. Technological development for human exploration and habitation of the Moon must necessarily focus on the creation of tools that allow for the utilization of the resources offered by the lunar environment.

Primary resources necessary for astronaut survival in a future lunar settlement are undoubtedly water and oxygen. Fortunately, oxygen is a key component of lunar regolith, comprising over 40% of its mass (Cesaretti et al., 2014). The presence of water molecules in lunar soil was suggested by the results from Deep Impact (Sunshine et al., 2009) and confirmed by mineralogical map from M^3 (Pieters et al., 2009): the impact of solar wind ions on lunar rocks was identified as responsible for the formation of these molecules, diffused along different latitudes but never consolidated in abundant deposits. Then, LCROSS mission identified the presence of water ice deposits in the Cabeus crater - lunar south pole - by analysing the ejecta of the impact of a rocket on the crater soil (Colaprete et al., 2010). That's why many human missions have been planned for the lunar south pole region: such abundant water stocks will be crucial for the support of a human mission.

Various studies have been conducted to understand how to extract these molecules from the lunar soil.

Among the processes for oxygen extraction from lunar soil, carbothermal reduction is favored (Troisi, Lunghi, and Lavagna, 2022; Gustafson et al., n.d.; Schwandt et al., 2012). NASA has conducted studies on the efficiency of oxygen extraction via carbothermal reduction through the Carbothermal Oxygen Production (CTOP) program (White and Haggerty, 2023). Moreover, the Carbothermal Reduction Demonstration (CaRD) project aims to increase the technology readiness level of a combined solar concentrator and carbothermal reduction system in a relevant lunar temperature and pressure environment (Paz, 2023). OHB-Italy and Politecnico di Milano have developed carbothermal reduction technology for extracting water and oxygen from lunar dry regolith (Pretto et al., 2023). Tests conducted on regolith simulants demonstrated the capability of extracting water and oxygen, with yields of up to 12% in feedstock mass and 25% in oxygen mass trapped in the dry simulant as oxides (Lavagna et al., 2023).

Beyond the extraction of basic resources from regolith, it will be necessary to create sustainable environments that can produce food and recycle waste. Various studies are being conducted on the development of Bioregenerative Life Support Systems (BLSSs): artificial environments that include multiple compartments designed to reproduce a self-regulating, chemically balanced ecosystem to support human life (De Pascale et al., 2021). De Micco et al. (2023) note that developing life support systems is a multidisciplinary and multi-generational effort, requiring expertise in fields ranging from microbiology and botany to system technology and biotechnology. As with the Apollo program, research and technological innovation in this area may have implications for resource sustainability on Earth. Fu et al. (2016) developed an artificial closed ecosystem, Lunar Palace 1, that integrates plant cultivation, animal protein production, nitrogen recycling from urine, and the bioconversion of solid waste. In 2014, a multicrew 105-day test demonstrated that the system could maintain habitable conditions, recycling water and oxygen and regenerating 55% of the food required.

Italy is also showing great interest in the area of food production in lunar environments: a collaboration involving ASI, ENEA, and G&A Engineering is currently developing a platform for BLSS experimentation. The SOLE project (*Sistema Ottico di illuminamento LED e controllo iperspettrale per la coltivazione di piante finalizzato ad applicazioni spaziali*) studies how combinations of LEDs at different wavelengths can induce plants to produce bioactive compounds in an automated and controlled system (ref. ENEAMedia).

3.4.2 Structures building and radiation shielding

Creating stable human settlements on the lunar surface also requires technological development in lunar construction. Cesaretti et al. (2014) proposed a technology for building habitats on the Moon using 3D-printed blocks of lunar regolith as construction material. Happel (1993) highlighted the promising mechanical properties of lunar cast regolith, which could be a valid candidate as a building material. Recent studies on regolith simulants have further investigated the structural properties, treatments, and logistical strategies for optimizing its use in construction (Toklu and Akpinar, 2022; Collins et al., 2022). Sik Lee, Lee, and Yong Ann (2015) experimented with a concrete made from regolith simulant mixed with a thermoplastic polymer, achieving a strength of 2.6-12.9 MPa within 5 hours. Although this method requires importing polymers from Earth, the concrete produced is strong enough to build relatively large structures, such as astronaut habitats.

Ferrone, A. Taylor, and Helvajian (2022) studied the feasibility of the *Regishell*, a structure composed of multiple layers of lunar regolith simulant mixed with binder materials recycled from landing missions. Monte Carlo simulations tested its viability as a radiation shield, demonstrating that layers of lunar regolith can reduce the astronaut radiation dose from solar particle events and galactic cosmic rays for a 14-day period. Radiation protection is indeed a critical aspect of lunar habitability and various studies on lunar regolith shielding properties have been conducted, focusing on both high-energy radiation from solar particle events (SPE) and galactic cosmic rays (GCR) (Miller et al., 2008), as well as secondary radiation like muons and neutrons (Meurisse et al., 2020). The findings are consistent with the estimates of Ferrone, A. Taylor, and Helvajian (2022). In this context, ASI has proposed a project for mitigating space radiation risks: the Autonomous Monitoring of Radiation Environment (AMORE) project. The aim is to go beyond standard detectors and develop a system that performs real-time analysis of radiation risks and provides astronauts with countermeasure recommendations (Narici et al., 2018). Such tools could be vital for future long-term lunar settlements.

3.4.3 Communication

Communication is a crucial aspect of all space missions. In lunar exploration, the communication challenge involves both Moon-based networks and Earth-Moon communication links. To support both, NASA and ASI are developing a constellation of micro-satellites orbiting the Moon. The project, called ANDROMEDA, aims to guarantee 24/7 global coverage with 24 satellites placed in 4 frozen elliptical orbits (Bhamidipati et al., 2023). Regarding Moon-to-Earth communication, Xiaorui Wang et al. (2014) proposed high bit-rate optical communication using ground-based telescope array receivers, while Ciaramella, Spirito, and Cossu (2024) suggested a link connecting a GEO satellite to a fixed Moon optical station. Another ambitious project for the creation of Lunar Communications and Navigation Services (LCNS) is called Moonlight (Sesta et al., 2023). Promoted by ESA and coordinated by Telespazio, this project aims to develop a satellite network in lunar orbit acting as GPS ones do. This network will be expected to support commercial and institutional missions by easing Earth-Moon communication and data downlink and providing communication channels for landers and rovers on the surface of the Moon.

4

Extended Reality

In this chapter, we present a description of *extended reality* (XR) technologies. These technologies, which once seemed futuristic or at least far from widespread adoption, are now gaining prominence in the lives of many individuals. According to Boland (2023), in 2023 there were approximately 1.41 billion active devices for augmented reality. Furthermore, according to the report by Fortune Business Insights (2023), the XR technology market reached a value of over 131 billion dollars in 2023. Projections in the report indicate a compounded average growth rate (CAGR) of 32.1% during the period 2024-2032. More conservative estimates by Statista (2023) suggest a market value of 41.22 billion dollars in 2023 and a CAGR of 10.77% for the period 2024-2028.

The increasing prevalence of these technologies, however, should not lead to misconceptions about the general public's understanding of their characteristics: in common parlance, terms like *virtual reality* and *augmented reality* are often used interchangeably. Despite the growing integration of XR technologies in leisure and professional activities, many individuals struggle to comprehend these technologies and their underlying principles.

We shall begin by elucidating the concept of XR and the various forms it takes in contemporary technology. According to Milgram and Kishino (1994), the different forms of reality can be positioned along an ideal continuum (Figure 4.1). At one end of this spectrum lies the real, tangible world, perceivable through all senses and impossible to completely forsake; at the other end lies the virtual world, digitally created, also perceivable through the senses (depending on the type of simulation), contingent on the performance of the software and

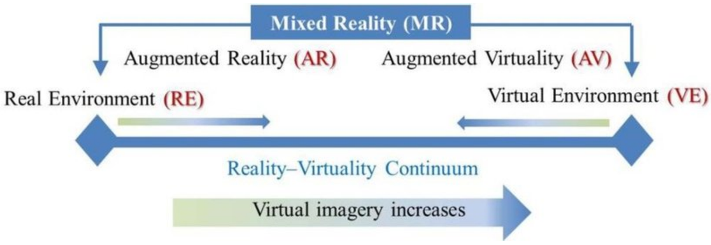


Figure 4.1: Reality-Virtuality continuum (adapted from Milgram and Kishino (1994))

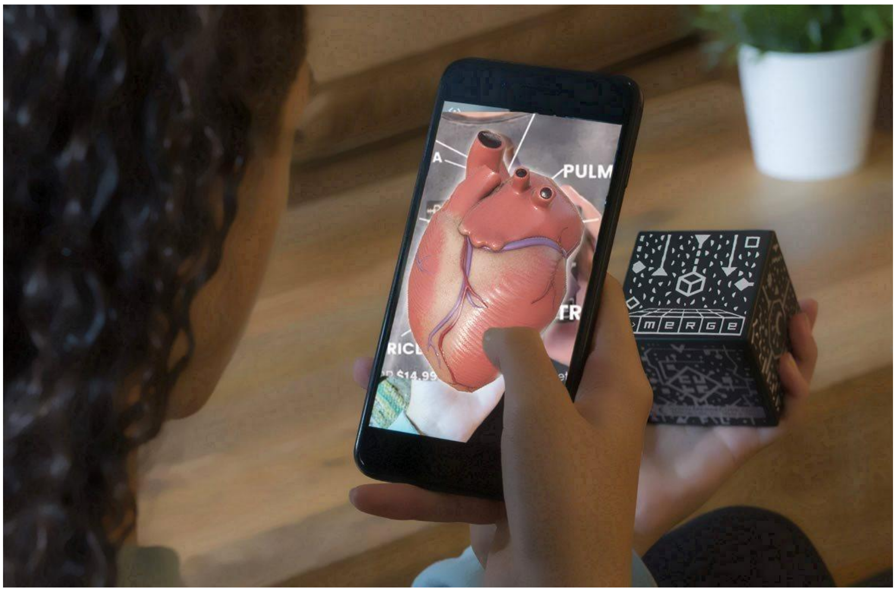


Figure 4.2: A student enjoying an augmented reality experience by a Merge-Cube. Credits:INFORMAWEB.IT

hardware that enable its implementation. Everything that falls between these two extremes is identified by Milgram and Kishino (1994) as *mixed reality*.

Within this categorization, the concept of *augmented reality* is positioned near the real world, involving the addition of virtual components within a given real context or its representation. In principle, the user can interact with these virtual components as well as with the real world, generating responses of varying complexity in the software managing the virtual components. An instructive example in this regard is provided by augmented reality experiences utilizing MergeCubes technology (Lin, 2023): by viewing this particular type of cube through the camera of a smartphone or tablet, the digital representation of the cube changes form, allowing interaction both digitally within the application and by moving the cube in the real world (Figure 4.2).

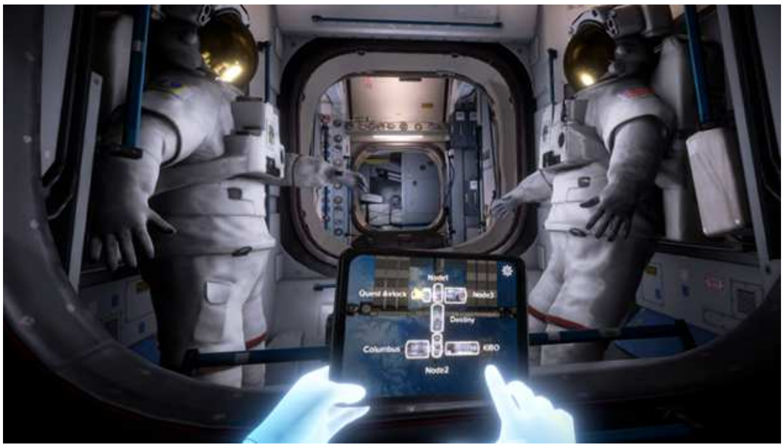


Figure 4.3: Mission ISS: a VR experience developed by Meta. Oculus Rift illustration - Credits: Meta

Milgram and Kishino (1994) also mention *augmented virtuality*, which involves the use of real-world content, adequately digitized and incorporated into the virtual world: examples of this include 360° renderings of specific real environments, which can be explored and navigated within the virtual experience (J. Jerald, 2015). The only aspect that differentiates this type of reality from pure virtual reality is precisely the real origin of the environments or content, which are acquired and then digitized through appropriate techniques – fisheye lenses, 360° recordings, photogrammetry – and finally uploaded into the virtual environment.

Pure virtual reality entails the creation of environments and simulation components from scratch (Figure 4.3), using modeling techniques and rendering processes (Subsection 4.1.1). The goal is often to immerse users to the point of completely detaching them from the real world (Milgram and Kishino, 1994).

The categorization presented above remains formally valid today. However, in terms of products development, marketing, and description of their fundamental aspects, a tripartite categorization is employed, distinguishing:

- augmented reality
- mixed reality
- virtual reality

In this framework, mixed reality becomes a type of medium that lies between augmented reality and virtual reality: the real world can be used as an environment or as an interaction mechanism, while virtual elements are presented to the

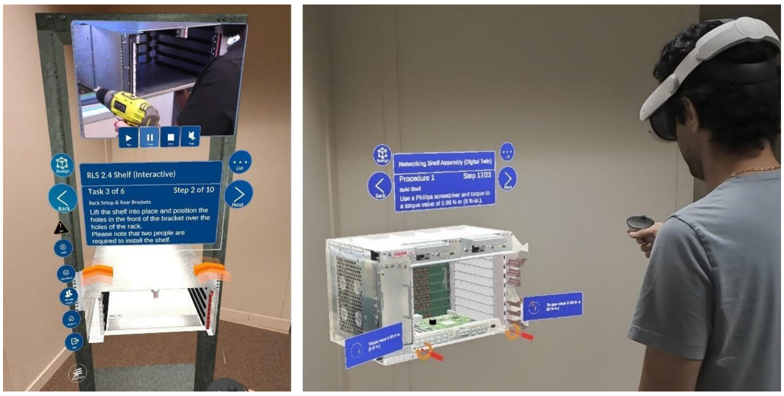


Figure 4.4: Enterprise training with a digital twin in mixed reality.
Credits: Arvizio

user with a level of immersion characteristic of pure virtual reality (Figure 4.4). In this sense, today, mixed reality assumes a value similar to what Milgram and Kishino (1994) referred to as augmented virtuality. However, today's technologies allow for a high degree of dynamic adaptation, enabling movement within the same experience along the continuum identified by Milgram and Kishino (1994), transitioning to an experience increasingly detached from the real world and closer to pure virtual reality or vice versa.

In the following sections we are going to present these three forms of extended reality. In Section 4.1, we address virtual reality, outlining its components and explaining the characteristics of each step that constitutes the operational cycle of a virtual experience. We address this technology for first because many aspects encountered in this description will be useful in subsequent sections. Section 4.1 is the most detailed, as the final product of this research work was created using this technology. In Section 4.2, we describe augmented reality technology, which is rapidly gaining traction across various contemporary sectors. Finally, in Section 4.3, we discuss Mixed Reality, understood as a combination of the two preceding technologies, which is rapidly advancing due to the development of components that enable software installation on relatively accessible devices. We conclude the Chapter with a discussion (Section 4.4) explaining the reasons that lead to the choice of VR within this research project.

4.1 Virtual Reality

J. Jerald (2015) observes that one of the difficulties encountered when attempting to define Virtual Reality (VR) is the semantic opposition between the two terms comprising this expression: as Sherman and Craig (2002) noticed, the word *virtual* is used to indicate the state of ”being in essence or effect, but not in fact” (Webster, 1989) while ”reality” indicates “the state or quality of being real” (Webster, 1989). To resolve this oxymoron, it is necessary to find a definition that encompasses both the experiential aspect characteristic of phenomenal reality (Radice, 1910), and the artificial, digital nature of the described object. Thus, J. Jerald (2015) defines virtual reality as a software-generated, interactable, and experienceable digital environment.

Sherman and Craig (2002) identifies four fundamental elements that characterize a VR experience:

Virtual World

The virtual world comprises all the digital elements generated by the software: the environment and the objects populating it. The objects are created from scratch using 3D modeling techniques and loaded into the software's memory during its development, along with the environment's details and various sensory stimuli. The ways in which the elements of the digital simulation interact with each other – the laws of the virtual world – are encoded within the software.

Immersion

The power of VR lies in its ability to immerse the user within the virtual world both physically and mentally. Mental immersion is linked to the suspension of disbelief and engagement, characteristics that other media also guarantee or seek: novels, films, and video games. Physical immersion is provided by the sensory stimuli present in the virtual world, which, unlike other media, reach the user in the first person. In a novel or film, it is the characters who receive stimuli from the world they inhabit, while the user perceives these stimuli only through the characters. In VR experiences, however, this mediation does not occur: the user receives the stimuli directly. The stronger the direct connection with the virtual world, the more powerful the physical immersion.

Sensory Feedback

One of the things we realize when interacting with an environment in the real world is that the environment appears different depending on the viewpoint from which we observe it. For the connection with the virtual world to be strong, this characteristic must also be respected. For this reason, in a VR experience, the software provides direct sensory feedback to the user based on their physical position. This is achieved through systems that track the user's movements and provide appropriate feedback according to coded instructions: if the user turns their gaze to the right in the real world, their viewpoint in the virtual world must change consistently with this rotation. We will see that there are different types of VR devices and, consequently, different tracking and response systems. For now, it is sufficient to specify that the systems must be able to track both the user's position in the real space and their orientation. Additionally, VR software must be designed to have a refresh rate of at least 60 Hz, otherwise, the sensory feedback would arrive with a delay perceived by the user as "unnatural," weakening the immersion's strength and, in some cases, causing significant discomfort.

Interactivity

Sensory feedback is not the only type of response that VR software can provide following user actions: the ability of a VR element to respond to user actions is referred to as interactivity. We speak of elements rather than objects because, in principle, even the laws of the virtual world or the sensory feedback can be made interactive during development. Interactivity is an element that immediately refers to the world of video games, where the user can use commands to interact with game elements and modify their properties, but it also perfectly adapts to the virtual world as a whole: the software continuously updates the state of the virtual world, with its elements and characteristics, in response to user actions.

According to our view, interactivity is the aspect that elevates VR experiences to a different level compared to those based on other media. Immersion and sensory feedback are fundamental for user engagement, but without interactivity, the user remains a spectator. Interactivity is the key to making them the main actor, the central point of the entire experience. By interacting with the virtual world, the user establishes a bidirectional, dialogical communication

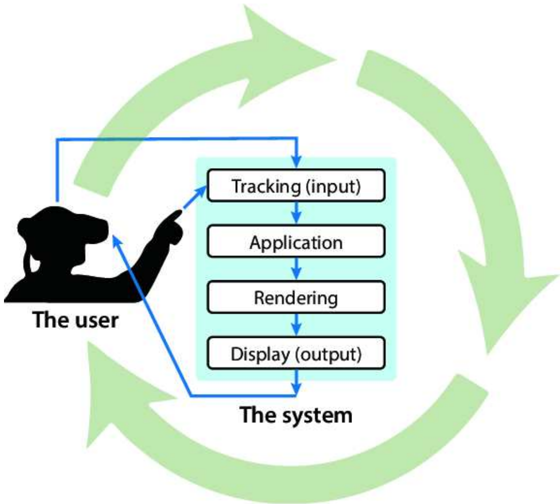


Figure 4.5: The VR-AR system input-output cycle (J. J. Jerald, 2009)

supported by the power of active and conscious choice. It is not the virtual world that informs the user; it is the user who questions the virtual world.

4.1.1 VR WORKING PROCESS

We have outlined the fundamental aspects that constitute a VR experience. We now proceed to delineate the generic workflow of the VR system (both hardware and software). The diagram shown in Figure 4.5, developed by J. J. Jerald (2009), summarizes the interaction between the user and the VR system and divides the system's operational cycle into four phases. We delve into the more technical aspects of VR systems following the order identified by the operational cycle.

1. Tracking and inputs

VR systems have many different ways of monitoring users's interaction with the virtual world: different methods in the tracking of user's movements and management of user's inputs define the different types of VR systems. Sherman and Craig (2002) state that both users movements and interaction with the virtual world can be defined as *inputs*. They also differentiate between:

- passive inputs: a pure consequence of the system monitoring of the user,
- active inputs: triggered by specific user's actions

Thus, *motion tracking systems* deal with passive inputs while *control systems* deal with active inputs.

Motion tracking systems are based on position sensors reporting their location and orientation to the central unit. Usually, devices include position sensors tracking the head - and sometimes the hands - of the user. This happens in both systems based on a headset projection and external projection (see **??**) as the head is used as an identifier of the user's position. Movements of an object in space have as many degrees of freedom (DOF) as the independent ways the object may move. Thus, in order to have a good realism, motion tracking systems must be able to follow user's motion along all the DOF. When a body moves in the 3D space independently of any constraint, possible movement can be reproduced in terms of six degrees of freedom: three rotational and three translational. We commonly identify with x, y, and z the axes around which rotations (orientation change) are performed and we use the same axes to build up a reference frame for translations (position change). Thus, six DOF tracking systems are able to reproduce all the user's movements. In some cases, only three DOF (rotational or translational) are required, for instance when the VR experience allows the user to look around without changing position.

Sherman and Craig (2002) notice the strong conflict among three aspects of position-sensing systems:

- accuracy, precision and speed in reporting the position,
- interfering media (physical objects or lights)
- space encumbrance

For instance, cable connected devices and cameras based tracking system provide fast and accurate position reporting to the central unit, but the presence of cables and the need for cameras line of sight and specific light condition affect the accessibility and the comfort of the VR experience. On the other side, low accuracy in the position and lag time may affect the realism of the immersion of the user or, in the worst case, induce motion sickness (Section 5.1). Modern position systems are designed taking into account the fragile equilibrium among all these aspects. Sherman and Craig (2002) discuss up to seven types of position sensor:

- **Electromagnetic tracking** operates by using a transmitter to create a magnetic field with three coils, inducing currents in a receiver unit worn by the user. The position of the receiver is determined by measuring the signals in its coils relative to the transmitter. Metal interference and limited range are drawbacks but this kind of system offers freedom of movement without line-of-sight restrictions.

- **Mechanical tracking** works by using devices like articulated boom arms to measure head position. Users can attach part of the device to their heads or simply hold onto it. The boom tracks their movements within a limited range, with each joint and link measured to determine position accurately. This method allows for quick and precise calculations using matrix mathematics. A drawback is that users are confined within a fixed location due to the physical linkages.

- **Optical tracking** utilizes visual cues, often employing video cameras or light-sensing devices. Computer vision techniques analyze the camera feed to determine the object's position. Multiple sources enable three-dimensional tracking via triangulation. Moreover, the combination of multiple visual inputs, such as three cameras, allows for full 6-DOF tracking. A drawback is the need to maintain a clear line of sight between the camera and the tracked object, restricting movement within the camera's view.

- **Videometric tracking** operates as a "reverse" optical system, with a camera that is attached to the object being tracked, observing the surroundings. The VR system analyzes the camera feed to locate landmarks and determine the camera's relative position. Distinct landmarks, as infrared light sources or bright colors recognizable shapes, serve as reference points in the environment. This approach needs a clean line of sight between the camera and all the landmarks.

- **Ultrasonic tracking** utilizes high-frequency sounds emitted at regular intervals to measure the distance between a speaker (transmitter) and a microphone (receiver). Similar to optical tracking, three transmitters and receivers enable the system to triangulate a tracked object's full 6-DOF position. Despite the low cost, this kind of system is low range limited, cable connection based and affected by noise, requiring an unobstructed path between speakers and microphones for accurate measurements.

- **Inertial tracking** relies on electromechanical instruments to detect relative motion. Accelerometers measure acceleration, while inclinometers gauge inclination. These instruments, along with gyroscopes, form self-contained tracking systems. Inertial sensors, attached to tracked objects, detect motion relative to a fixed structure and transmit data to the central unit. This kind of system is capable of measuring full 6-DOF motion though it may introduce drift, which requires occasional manual realignment. Despite such a limitation, inertial trackers offer benefits like portability and low latency. They are often integrated into head-based displays, providing quick orientation tracking. Combining inertial tracking with other methods like magnetic tracking can enhance accuracy and reduce drift.

- **Neural or muscular tracking** involves sensing individual body-part movements relative to another part of the body, rather than tracking the user's location in the venue. Sensors attached to fingers or limbs measure nerve signal changes or muscle contractions, reporting the posture to the VR system. This tracking method has not been extensively explored and, due to the high level of technology it uses, it has never been used in the public outreach field.

We call *control systems* all the physical input devices that serve as interfaces between users and virtual world. Control systems include buttons, switches, and valuators, enabling users to provide direct input into VR systems(Sherman and Craig, 2002). Systems can be generic or designed for specific applications. They can be mounted on platforms, handheld devices, props or elsewhere in the venue. Simple control systems have discrete positions or states, like buttons with two positions: depressed or released. Switches offer multiple positions. Handheld devices, named *controllers*, often feature multiple buttons for event triggering and valuators providing continuous control with single or multiple DOF. *Joysticks* are 2 DOF valuators commonly used in the videogame field and also VR controllers usually feature this kind of input system. Controllers provide various types of inputs and the combination of versatility and ease in using makes them the most common control system in modern VR devices. Moreover, they are usually subjected to tracking: altough they are not cable connected with the central unit, in many cases controllers are equipped with position sensors giving the VR system the possibility to track their movement and orientation.

As a consequence, VR systems with trackable controllers provide a *point and click* input system in the virtual world.

Within the broad variety of VR systems it is possible to find also some control systems that do not need any particular device but the tracking system itself. Modern optical and videometric systems are able to track the movement of the hands of the user. Hands may substitute the pointing function of the controllers while fingers' relative position are used to provide inputs. This *hand tracking* input system is implemented in a more complete sense in some VR systems by the use of specific devices as trackable gloves. By following the same approach and adding other position sensors, the tracking can be extended to every part of the body. However, in order to provide basic inputs, a simple hand tracking system is sufficient. Moreover, some modern devices are able to perform hand tracking without gloves or specific sensors. This is the case of the Meta Quest 2(Section 5.1), using inside-out cameras to detect the position and orientation of the hands and the configuration of the fingers. Even simpler is the *eye tracking* input system: the orientation of the head is used as a pointer while triggering works on a time-lapse based method.

It is crucial to note that both controller based and tracking based active inputs systems work as an interface between the user and the virtual world generated by the software. This means that input systems are strongly connected with the user interface of the software. Thus, it is time to move to second aspect of the VR operational cycle, giving an overview of the software component.

2. Application

The development of a VR experience primarily involves designing and implementing the processes that occur during this phase of the operational cycle. Once the inputs, whether active or passive, provided by the user are acquired, the VR system processes the feedback to be returned to the user. The way in which the system responds to specific inputs is encoded in the software, although some hardware limitations may constrain the system's response capabilities to certain types of inputs: for example, hardware that supports 3 DOF tracking limits the software's ability to process responses to translational movements. Conversely, a device may have highly advanced hardware for input reception while being limited in terms of software capabilities. This highlights a crucial aspect of VR instrumentation: processing (application) can be performed by a separate computing unit that receives inputs from peripheral sources and provides outputs to display systems. In such cases, the software runs on a central unit, usually a computer with a high-performance processor, and typically includes a dedicated graphic processing unit (GPU) to handle rendering. This is not the case for standalone devices (such as the Meta Quest 2), which autonomously manage all phases of the operational cycle. Therefore, when developing a VR product, it is essential to consider the support platform on which the software will operate: software requiring significant computational power may be challenging to manage on a standalone device. Equally important in development is software optimization. The operational cycle of a VR system is iterative, repeating multiple times per second, and it is crucial that the software can process all data and provide the corresponding feedback with appropriate instructions at each step of the cycle. If the computational load is too high or the number of instructions is excessive, there is a risk that the software may require too much execution time for each step: this can lead to lag, which in VR experiences can cause disorientation and motion sickness.

3. Rendering

Rendering is the creation of sensory images representing the virtual world. In order to perform a high impact immersion within the virtual environment, such images need to be perceived as a continuous flow. Moreover, rendering must be real time sensitive to all kind of interaction between the user and the virtual world. In the following we are going to focus on visual rendering: general considerations keep true also for haptic and aural representation, but the actual use of these kind of stimuli for the representation depends on the design of the experience. Most of the times, visual representation is the the main one for most of the entities populating the virtual world, while sound and haptic sensations are provided as details in order to lead the user to a deeper sense of immersion.

As vision is considered to be the primary mean we have to get information about the physical space and the objects around us, it keeps a primary role also in VR: by visual perception users are able to relate their position with to other entities and keep themselves oriented within the virtual space. Distances from different objects can be inferred by some of their visual characters and attributes and this allow users to have cognition of the space and to build up a mental map of the world they are moving within. Thus, rendering the virtual environment and the objects that populates it constitutes the first step to guarantee a good level of immersion and comfort. Moreover, visual elements are fundamental as user-interface tools, leading users interaction with the virtual world and providing instruction and control systems support. Depending on the role an element assumes within the virtual world, the rendering may be realistic (or pseudo-realistic) or figurative: in the first case, the element mirrors the characteristics it would have in the real world, while in the second case the representation is essential and direct. In both cases we can have a dynamic rendering: objects may change their position, orientation, motion with respect to the virtual world, and the representation must be sensitive and adaptive to such changes.

Hardware and software systems are used to transform computer representations of the virtual world into signals sent to the display devices. The whole set of hardware that is optimized to perform the computations needed to generate the rendering is called *rendering engine*. The software rendering system includes all the graphical rendering routines and formats implementing the representation. Such instruments elaborate files consisting in pre-built graphical shapes or instructions to generate graphical shapes. Thus, software has to manage schemes describing space and objects in order to transform their digital representation into a 3D-shape displayed representation.Sherman and Craig (2002) differentiate between Geometrically Based Schemes (GBSs) and Non-Geometrically Based Schemes (NGBS). GBSs result particularly suitable for the representation of solid, non-trasparent objects, as they work reproducing the shape of the object. We have three main GBSs:

- **polygonal method**, a representation of 3D objects by a series of line segments that define edges and faces;
- **non-uniform rational B-splines** (NURBS), a parametrical represetation of curve shapes;
- **constructive solid geometry** (CSG), using sum and subtraction of simple solid shapes to build up 3D objects;

On the other side, when we need to render objects characterized by specific features in the interaction with light (transparency, translucency, diffusion), surface based rendering must be substituted by a volumetric representation. *Volume rendering* is performed using ray-tracing and ray-casting techniques, taking into account the characteristics of the materials of the objects: light rays interaction with different materials are codified within the files that describe materials, and the software perform multiple calculations to manage all the interactions. This is a very expensive method in terms of calculations and a powerful hardware is needed to perform such representation real time. Clearly, volume rendering guarantees an high level in the realism of the representation, as well as particle system rendering: a method that exploits the rendering of many small particles to produce a large scale phenomenon visual representation(Reeves, 1983), e.g. explosions, fire, water flows. However, the high computational cost of volume and particle systems rendering compromise the efficiency that we identified as a crucial quality for every step of the VR operative cycle. Thus, a combination of GBSs and NGBs is commonly used in the rendering of the virtual world, depending on the complexity of the scene that is rendered. *Shading* is one more aspects that contributes to the composition of a complex scene: it deals with how light is reflected off objects and reach user's eyes, regarding both GBS and NGBS rendered objects. Managed by the software, a suitable use of shading is able to provide realism and deepness to a scene despite the limitation of the hardware. Another trick to manage a large complexity scene without requiring high computational power is constituted by the use of *texture mapping*. This technique consists in simulating by surface features the details of the objects that would be too expensive to reproduce by a GBS: for instance, the roughness of a wooden object may be simulated by a flat surface with a texture rich of stripes. This reduces the number of polygons that are needed for the rendering of the scene but preserve the 3D shape of the wooden object, at least from a visual point of view. Pre-rendered images - Image-Based Rendering(IBR) - weaves, non-uniform colors, transparency, reflectivity and many other features may be mapped as texture, expanding the potential of the rendering beyond the limit of the actual geometry of the objects. Finally, the *culling* technique eliminates the polygons that are not visible in the scene, as the ones that build objects located partially or totally out of the field of view of the user. Alternatively, culling may operate dynamically, modulating the shape of an object depending on the level of detail that is needed for the rendering: for instance, when an objects is very far from the the user in the virtual world, but still in the field of view, it would be a total waste of computational resources to reproduce it with a high level of detail; the culling allows to simplify the shape of the object, as long as it remains far from the user, and to restore the original shape whenever a close-up visualization of the object is needed.

4. Display

VR displays are the means by which users are physically immersed in a virtual world. As we saw in the Subsection 4.1, achieving mental immersion requires a strong emotive involvement of the user: such a sensation can be fostered by display of the virtual world to multiple senses(Sherman and Craig, 2002). We briefly explore hapitc, aurual and visual display solutions. Different senses contributes in a different way to global perception of the world. Thus, visual, aural, and haptic feedback need different rendering and display requirements, in particular for what concerns temporal resolution. For visual display an update frequency of 24 Hz results acceptable to provide a sense of continuity, while haptic display needs a frequency around 1000 Hz (Massie, Salisbury, et al., 1994). Aural display provides different quality of the sound depending on the update frequency: a value of 8 kHz provides a telephone-quality sound while a 96 kHz one guarantees a quality similar to the one we can find in modern Blu-Ray devices.

While it's challenging to replicate haptic sensations accurately, such feedback enhances the realism of VR experiences. The primary methods of haptic interface in VR applications include tactile displays, end-effector displays (for simulating grasping and probing), robotically operated shape displays, and 3D hardcopy models. Their goal is providing tactile sensations, simulating limb movements, presenting physical objects, or creating physical models based on virtual ones. Actually, these solutions are usually implemented independently from VR, but there's potential for including them within some VR systems. Due to the presence of specific physical object, this kind of approach lies beyond the limitation of VR and may be included in the field of Mixed Reality. Thus, we decide to stop from going deeply in the description of haptic display solution.

Aural displays' world is commonly split into two main categories: *head-based displays*(HBD) and *stationary displays*. HBD include all the different kind of headphones providing direct aural stimuli to the user's ear, providing a good restitution of sterophonic sounds. In some cases, when sounds come from a specific source in the virtual world, displays must be able to consider the head tracking in order to provide the right sound feedback in response to the movements of the user: this aspect is usually managed by the software. Real world sounds can be sealed off by closed-back headphones while open-back ones allow the user to hear both real and digital sounds. Headphones display head-referenced sounds by default. When sounds in a 3D virtual world should appear to come from a particular location, it is important to track the head position of the participant so that spatialization information reflects the changing location of the listener's ears. Unlike wearing headphones to listen to stereophonic music, in a virtual reality experience, the sound stage should stay registered with the virtual world. This requires tracking the participant's head and filtering the sound appropriately.

A similar splitting affects also visual displays: we can find Head-Mounted Displays (HMD) and World-Fixed Displays (WFD). J. Jerald (2015) mentioned also Hand-Held Displays, but nowadays it is impossible to find VR devices characterized by such display approach, while it results suitable for augmented reality. HMDs allow the tracking of the position and orientation of the user's head. Low latency response of the display system to the tracking ensures an effective sensory feedback: as the user's head moves or rotates, the point of view and the perspective on the virtual world changes and a different visual stimulus must be displayed(J. Jerald, 2015). Obviously, such stimulus is limited to the actual field of view of the display and it is not necessary to display the whole virtual world in every frame. Certain types of HMDs enable users to perceive both the real and virtual environments. This functionality is facilitated, for instance, by the integration of a camera directly mounted on the HMD. Nonetheless, only specific devices possess the capability to concurrently render the camera feed and the virtual environment: these devices are specifically optimized for mixed reality applications.

WFDs usually consist in one or more surface where visual stimuli are projected or digitally reproduced. Monitors are the simplest WFDs, while multi-surface solution overcome the limitation of the field of view: this is the case of the CAVE-type displays, constituted by three or more surfaces surrounding the user. This kind of solution allows for a large field 3D displaying of the virtual world. Moreover, head tracking is not required as stimuli are usually not related with user's motion(J. Jerald, 2015). In fact, WFDs sensory feedback is performed in response to user's active inputs.

4.2 Augmented Reality

Augmented reality is obtained starting from real elements, exploiting technologies like QR codes, barcodes, specific triggers, to activate applications, tools, web pages, holograms, and general digital contents in order to expand the quantity of information about these elements. AR applications run on common devices like smartphones and tablets, leveraging their cameras to scan triggers. This makes AR much more accessible to the general public and often simpler to use. Referring back to the fundamental components of a VR experience listed at the beginning of Section 4.1, we can find similar elements in AR, particularly regarding interactivity: in AR, this operates on both the real and virtual planes. In many AR experiences, interaction is primarily with the triggers in the real world, while the additional digital content is often consumed passively or with limited engagement. Examples of this approach include infographics and audio guides that accompany audiences during festivals and museum tours. Sensory feedback and the virtual world continue to play a role, although their significance is clearly diminished and more constrained in this type of media. The experience starts with the real world, and it is in this context that elements become experiential, interactive, and augmented: the virtual element is an addition, an enhancement, something that is central to the experience aesthetically and narratively, but remains subordinate to the real element. Sensory feedback also has a much more limited dimension: visual and auditory stimuli are crucial for capturing and maintaining the user's attention on the content but only provide a very focused perspective on what is being interacted with. For example, in an environment with various triggers for an AR experience, it is challenging to implement mechanisms where sensory feedback encourages the user to explore the environment, transitioning autonomously from one augmented element to another: essentially, unless high-level user experience techniques are used or the user is explicitly guided, it is difficult to convince them of the existence of an *augmented world*. Not surprisingly, immersion is the element that characterizes VR experiences and is virtually absent in AR experiences.

4.2.1 AR Working Process

Starting from the VR operational process mentioned in Subsection 4.1.1, the only step in the iterative cycle that is profoundly different in AR compared to VR is related to inputs. In reality, in some cases, the unconditional iterativity of the process is absent, and each cycle starts only in response to a specific type of input: for instance, in an AR experience based on infographics activated by scanning QR codes with a smartphone, the activation process for a single infographic begins with the scanning (input) and concludes with the display on the screen, which remains active until the next scan. The AR experience has the real world as its setting and the first level of the interaction (triggers) happens in the real world ; thus, tracking is not necessary in this context. In VR experiences, tracking is used to create a connection between the user's movements in the real world (passive inputs) and their effects in the virtual world (application and rendering). In AR experiences, there is no need to track user movements because the use of cameras serves as the bridge: the AR software does not need to know the precise movements of the user; it only needs to know whether the user has interacted with a trigger (input) or not, to activate the additional content (application), process it (rendering), and present it to the user (display). We might describe this as a form of videometric tracking, except that the underlying concept is quite different: tracking allows for continuous passive input from the user and updates the system's response accordingly; scanning triggers is by definition a discrete process, so even if the system receives continuous passive inputs, it is the active input from scanning that provides the software with the necessary information to proceed with the subsequent phases.

Regarding application and rendering, there is continuity with what was mentioned in Section 4.1, although specific approaches may be followed depending on the type of application being developed: rendering an infographic is much simpler than rendering an animated 3D reconstruction of a digital twin of a real object. Certainly, compared to virtual reality, the limited number of digital elements to be loaded from scratch, processed, managed (in terms of interactions), and rendered results in much lower computational costs. While high-performance, separate processing units are quite common for VR technology, AR benefits from its relative simplicity, functioning effectively even on less powerful devices.

4.3 Mixed Reality

Today, Mixed Reality (MR) is understood as a blend of Augmented Reality (AR) and Virtual Reality (VR). In some respects, it is challenging to draw a clear demarcation line between MR and simple AR, as both are predicated on starting with the real world and adding virtual content. MR dynamically positions itself along the continuum between the real world and the virtual world, and this is likely its distinguishing feature: in a pure VR experience, the user is entirely

Figure 4.6: Screenshot of a video showing the gameplay of the MR experience *First Encounters*.
Credits: TmatTn2 (https://www.youtube.com/watch?v=BM0CZUHrbcw)

disconnected from the real world and interacts solely with the virtual environment. Conversely, in an AR experience, the user engages with elements of the real world, and only subsequently is virtual content introduced, which never completely pervades the experience. MR technology enables users to traverse the spectrum connecting these two types of experiences: an MR device can support applications that display elements of the real world and expand the content through the addition of virtual elements, but it can also separate the user from the real world and fully immerse them in a virtual simulation.

Thus, the fundamental components of an MR experience and the operational flow are the same as those seen in the previous sections for VR and AR. A crucial aspect is the integration of the two passive input methodologies characteristic of VR and AR: the tracking system and the camera. When dealing with a virtual space (virtual world) that can be accessed, explored, and interacted with at various levels of depth, tracking the user's position and orientation is essential. On the other hand, cameras allow users to maintain visual contact with the real space and its elements. Having high-resolution color cameras is crucial for maintaining a strong connection with the real world, while the tracking system must relate the user's movements to the virtual environment while accounting for the characteristics of the real-world spaces, objects, and details. MR systems must enable spatial mapping of the real environment, including boundaries, obstacles, different depth levels, and specific distances between objects, and must be capable of tracking the user's movements even within arbitrarily complex spatial contexts. An example of an MR app is shown in Figure 4.6. In the upperright corner, we can see the user in the real world - a typical living room. The main screen, however, shows what the user sees within their headset: a faithful reproduction of their real space - the same living room, captured in real time by the device's camera and rendered in response to tracking movements - with a virtual cartoon-style spaceship inside, complete with a fuel jet, smoke, and debris released from its entry through the ceiling. In the experience, the spaceship moves throughout the virtual environment, circling around the user, hiding behind real-world objects, and hitting the walls. This type of experience diverges from pure VR as the setting is the real world, but it is also quite different from pure AR since the virtual objects are not activated by triggers present in the real world: the real and virtual worlds merge, creating an experience that is, in some respects, even more evocative than pure VR.

4.4 Discussion

In order to conclude this chapter we provide final considerations about the different XR technologies, explaining why we opted for the development of a VR experience. We excluded a priori MR because when this project started devices for MR were very expensive and less performing with respect to VR ones. Moreover, MR experiences need a larger quantitative of effort in design and development processes as they are explicated on the both levels: real world and virtual world. Nowadays, devices that support MR are more accessible - Meta Quest 3 was launched on the market in 2023 - but the use of a different technology needs a complete restyle of the experience in terms of design.

Considering accessibility as a crucial point, one may think that AR provides the best opportunities. A great advantage of AR technology is that users can receive information on their own devices and meanwhile keep on relating with the real object of interest. It's easy to understand that this technology has a lot of potential applications in the sector of museums and didactic activities. Moreover, as it is based on real elements, an AR experience is naturally accessible by groups of people, encouraging dialogue, debate and ideas exchange in the real life. On the other hand, the strong connection with actual reality make harder to exploit AR in the field of astronomy: this kind of experience gives its best when allows to expand information about something that lies close the user, when the real, actual, touchable element is completed from additional information and aspects. Except for telescopes, instruments, and museum pieces, everything that is interesting for astronomy is very far from the user. This is an important limit for the use of AR in astronomy outreach.

VR has the advantage of the building from scratch: in a pure virtual environment it is possible to reproduce any kind of setting and also to populate it with any kind of object that the experience needs. Moreover, the immersion in the virtual world provides wonder and immediate interest in users, separating them from the distractions of the real world. From an emotional point of view the power of VR is definitely stronger with respect to AR and thus the engagement of users exploring a different world keep feeding itself by the dynamical proposal of stimuli and possible interactions. For sure, the larger is the number of objects and the level of realism that the developer aims to provide, the higher is the level of the performance hardware and software must guarantee. Thus, highest realism virtual experiences are not supported by stand-alone devices and need a central unit for the elaboration. Clearly this is a strong limitation in terms of accessibility: an experience that needs an high level of hardware and software to run is expected to reach a limited number of people. A possible solution consists in providing everything that is needed to run the experience - setting up a *VR work station* - within public spaces: science festivals, in person tours, classroom demonstration are some of the suitable contexts for this kind of installation. The logistics problems connected with the necessity of such kind of working station include: material transport, spaces management, setup, technical management. Moreover, the problem of the low number of users, also in public contexts, is endorsed by the fact that all the VR devices that operate with HMD support only single users, while CAVE systems must be very cumbersome in order to support a higher number of users at the same time.

In order to reach a compromise among accessibility, emotional engagement, interactivity, and astronomical setting, we decide to develop a VR product running on a low-coast standalone device. In the beginning of the next chapter (Section 5.1) we are going to describe the characteristic of the selected device fostering this kind of approach.

5

VR product: process development

In this chapter, we describe everything related to the virtual experience developed as part of this project. In Section 5.1, we describe the VR device for which the experience was developed. In Section 5.2, we discuss the development framework for the virtual experience: Unity. The information contained in this section is highly technical, but it is necessary to understand how the various aspects of the virtual experience were developed. The actual development is addressed in great detail in Section 5.3. Finally, Section 5.4 describes the feedback from the beta-testing process, highlighting the issues encountered during this phase and the ways in which they were resolved.

Figure 5.1: Meta Quest 2: headset and controllers

5.1 VR Device: Meta Quest 2

There are many virtual reality devices on the market. In particular, the Meta Quest 3 has superior potential compared to the Meta Quest 2 in terms of graphics and computational power. However, this device had not yet been released when the project for this work began. The virtual experience was developed from the outset for the Meta Quest 2, which offers a good compromise between performance and versatility, as we will see below. We will therefore present a description of this device: for more detailed information, see the *Meta Quest 2 manual* (n.d.).

5.1.1 Components and Specifications

The Meta Quest 2 (Figure 5.1) is a virtual reality device that has been on the market since October 2020. The device consists of a headset and two controllers. After describing the characteristics of these elements in their respective subsections, we will move on to the description of the hardware and software.

Headset

The headset is a type of mask, worn using a stabilization strap. Its dimensions are 450 mm x 224 mm, and it weighs about 500 g. Most of the hardware of the device is concentrated in the headset, protected by a rigid shell on the outside. The inside, which comes into contact with the skin of the face, is soft and shaped to optimize comfort and fit. The lenses through which the three-dimensional vision occurs are placed at an adjustable distance depending on the user's needs. The same applies to the stabilization strap that keeps the headset steady on the user's head, adjustable with straps at the back and a hook-and-loop fastener for the top. Besides the power button, the headset has two buttons for volume control: there are speakers for 3D positional audio playback, as well as a 3.5 mm audio port for adding optional headphones. The headset is equipped with a 3640 mAh rechargeable lithium-ion battery with a power of 14 Wh.

Controllers

The controllers are designed for a pistol grip. Both are equipped with a trigger-shaped button corresponding to the index finger and a second button (the *secondary trigger*) corresponding to the middle finger. The thumbs rest on the flat part of the controller, where two more buttons are located, named *X* and *Y* for the left controller and *A* and *B* for the right controller. An analog stick (*joystick*) that can be operated with the thumb is present on both controllers. The *General Menu* button is located only on the right controller, while the *Menu* button is its counterpart on the left controller. The controllers are powered by AA batteries (one for each controller).

Technical Specifications

At the hardware level, the device is equipped with a Qualcomm Snapdragon XR2 Gen 2 processor, 8GB of RAM, and internal storage of either 128GB or 256GB. The display is a fast-switch LCD with a resolution of 1832x1920 pixels per eye. The device supports refresh rates of 60, 72, and 90 Hz. On the software side, the device supports an Android-type Oculus OS system. This is an all-in-one device that does not require an external processing unit. Virtual experiences are loaded into memory in Android PacKage(APK) format, and once launched, they are processed by the central unit housed in the headset. It is therefore evident that one of the advantages of this type of device lies in the fact that no cables are needed for power or data processing. On the other hand, the processing capacity and resolution of the content are limited by the relatively modest power of the hardware. The device is equipped with a 6-degrees-of-freedom (6DOF) tracking system (3 translational and 3 rotational) for both the headset and the controllers (see Section 4.1.1 in Chapter 4).

5.1.2 Functionality

The brief description of the hardware presented above offers a portrait of the Meta Quest 2 from one perspective. Certainly, these elements influenced the choice of the device: the resolution of the Meta Quest 2 allows for a decent level of realism and detail in the content, while the refresh rate ensures good fluidity in visualization and interactions even in relatively complex virtual environments. However, the aspect that most influenced the choice of this device is undoubtedly its versatility. The fact that the Meta Quest 2 does not require a central processing unit, along with the complete autonomy of tracking, is an undeniable advantage in terms of accessibility. Experiencing the virtual world simply by wearing the headset and holding the controllers, without the need for a specific setup, greatly reduces the public's hesitation in favor of the intrinsic curiosity that the use of a technological device brings. The ease of configuring the virtual space and the use of basic commands makes the work of those proposing the experience much simpler, while also accommodating users who are not accustomed to using VR devices.

Space Configuration

Thanks to the tracking functionality, the user can physically move and use their hands, generating a reproduction of those same movements by their avatar (at a basic level, a virtual representation of the headset and controllers) in the virtual space. It is important to note that the tracking capability of the headset is limited: when the user wears the device, they are asked to place a controller on the floor so that the system can calculate the correct height of the headset from the ground. After that, they are asked to define the boundaries of the virtual room. These can be manually traced by the user (*Manual Boundaries*) or automatically calculated by the headset based on the dimensions of the real space where the device is being used (*Roomscale*). The headset is equipped with a black-and-white camera that allows the user to see the real space during the manual room configuration phase; using this same camera, the device can automatically recognize the presence of objects within the manually defined room and suggest that the user remove them or define the virtual space differently; similarly, the system can autonomously define boundaries for the virtual room based on the limitations present in the real space (walls, large objects, etc.). Regardless of the boundary configuration method used, the virtual room space never exceeds 30 m^2. Once the boundary definition is complete, the user can access the headset's main screen, *Oculus Home*, configure specific settings, launch applications, and fully utilize the device. If the user approaches the boundaries of the virtual room, the device signals this by highlighting the boundaries themselves in the form of a colored grid. If the user crosses the boundaries, tracking and controller functionality are suspended, and an error message is displayed, instructing them to return within the boundaries.

Basic Controls

The display is panoramic and three-dimensional, and navigation can be done using the controllers through a pointing and selection mechanism: one points

the controller in the direction of the icon corresponding to the application they want to launch and select it using the *trigger*, *A*, or *X* buttons. The *B* and *Y* buttons allow them to return to the previous screen. The *General Menu* button opens or closes the main screen's menu, which is a toolbar displayed in front of the user. The Meta Quest 2 also supports hand tracking. This pointing system must be specifically configured in the device settings as a replacement for the controllers. Selection, in this case, is done by bringing the tips of the index finger and thumb together.
It should be noted that room configuration, the display of the *Oculus Home* screen, and the launch of the virtual reality application are preliminary operations that are not part of the *Moon VR* experience, but are implemented in the device's operating system. The same applies to the basic controls listed earlier: the validity of these controls applies to the operating system environment (main screen, settings, etc.). Applications installed on the device are programmed with an autonomous command system in principle: this means that within an application, the various buttons may have different functionalities from those valid in the operating system. The exception is the *General Menu* button, which has universal visibility and, even when pressed during the running of an application, pauses the application and restores the validity of the operating system commands.

Connectivity

The device can be connected to a WiFi network. Additionally, it is possible to download a smartphone app that helps manage the headset and its settings. To allow this app and the device to communicate, both the device and the smartphone must be connected to the same WiFi network. The smartphone app is also one of the methods through which to perform the *mirroring* of the device. Mirroring refers to displaying on a screen what is being reproduced by the headset. Mirroring can be performed on other types of screens without using the app as long as they are also connected to the same network as the device: it is possible to use casting devices to connect the screens or perform mirroring from a browser when viewing on a PC. Alternatively, mirroring can be done via cable. The headset is equipped with a USB-C port used for charging and connecting to a PC. Cable mirroring has the advantage of being much more stable and less prone to lag, but it carries the disadvantage of requiring a wired connection, thus negating one of the strengths of this device.

5.2 Unity

Unity is a development environment for designing video games and applications across multiple platforms, first released in 2005. Beyond providing a graphics engine that renders the visual elements of an application, Unity offers integrated development tools to manage physics, lighting, sound, and user interactions. This greatly simplifies the developer's task, as much of the programming is eluded by relying on pre-developed tools. This type of structure is known as a Game Engine: a framework that provides reusable software components, easily accessible through intuitive visual tools. These tools invoke pre-loaded and pre-compiled scripts written in $C\#$, the programming language supported by Unity. While these scripts are accessible to developers, they are not editable; however, developers can include or exclude tools as needed for their development. Developers can create custom scripts to implement new functionalities; these scripts must be compiled, and any errors prevent the application from running, even in preview mode. Unity allows for preview testing of the application within its development environment and enables small real-time modifications to monitor the application's behavior.
A brief note on terminology: while we use the term "application" for clarity and convenience, the application is actually the end product of the development process. During development within Unity, it is more accurate to refer to it as a *project*. A project becomes an actual application when it undergoes the *building* process, which converts the project into a specific file ready to be launched on the platform for which it was developed. A project consists primarily of: general settings, scenes, and assets.

General Settings
These are settings that apply to the entire project. They can be divided into two broad categories:

- Development Environment Settings: Interface, drivers, pre-loaded Unity tools and packages.
- Final Application Settings: Framerate, building format and settings, rendering quality.

Many other aspects can be managed within the settings, but discussing the specific features and potential of Unity goes beyond the objectives of this thesis.

Assets

Files that are part of a project (images, 3D models, scripts) fall under the common designation of *assets*. Different types of files correspond to different types of assets. We will refer to various examples of assets in subsequent sections when discussing the elements that make up the scenes and their characteristics.

Scenes

A scene encompasses everything that is present (and potentially visible, audible, or interactable) in the application until transitioning to the next scene. The sequence of scenes is coded in one or more scripts created specifically by the developer. Scenes are developed one at a time within Unity's editor, each structured in its own virtual space with specific settings for ambient lighting and background. The elements present in a scene are called *objects*. Objects are the fundamental building blocks of any application: they can belong to various types and be equipped with different *components*. Components constitute specific properties of an individual object. The scene development environment is organized into several interactive windows: the object hierarchy (*Hierarchy*), visual scene editor (*Scene*), object properties viewer (*Inspector*), project preview (*Game*). Additionally, there is a window for viewing the project divided into files and folders (*Project*) and a *Console* where compilation and/or debug output can be viewed. Figure 5.2 shows a screenshot of the MOON RESCUER development environment.

Having outlined the characteristics and development context of the units that make up a project – the scene – we choose not to proceed with a detailed description of all types of elements and properties that can be included in a scene. Such a description would make the reading cumbersome, and it is preferable to move directly to the next section, where the scenes that make up the MOON RESCUER product and their development processes are described. In the table 5.1 , we provide a very basic list of the elements used for the development and their components and functionalities, referring to Appendix A for a detailed description.

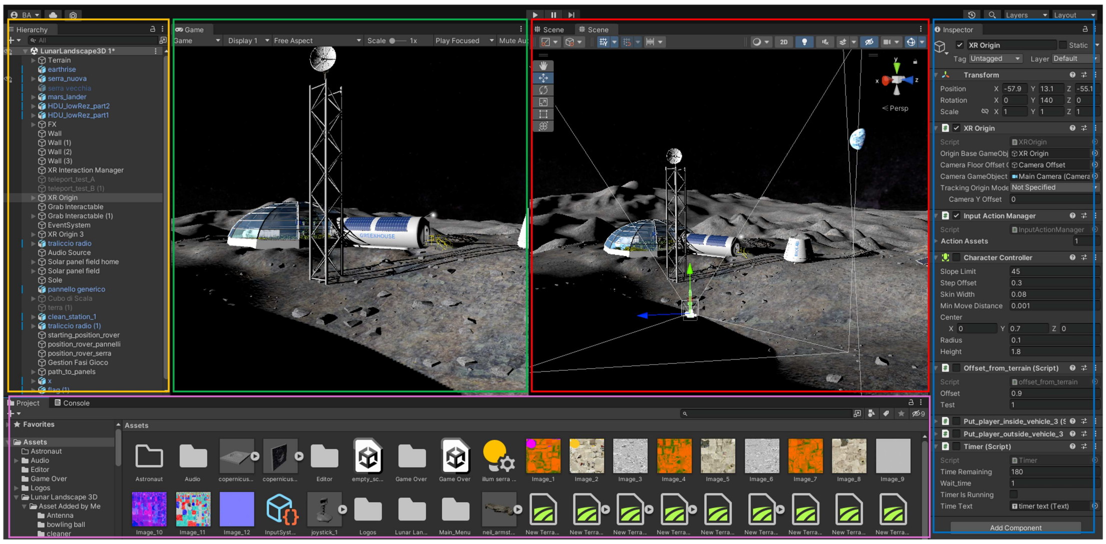


Figure 5.2: Unity window screenshot during the MOON RESCUER project development. The various windows are highlighted by different box colors: Hierarchy (orange), Game (green), Scene (red), Inspector (blue), Project (purple).

5.3 Application Development

After presenting the development environment, it is time to focus on the product itself: the VR application developed for this project, named *MOON RESCUER*. Many aspects that characterize the final product were modified during development in response to emerging bugs, issues with interaction with the environment and objects, and generally any situations that could cause discomfort for the user. Despite this dynamic workflow, some fundamental premises remained valid from the beginning to the end of development. The virtual experience needed to be characterized by:

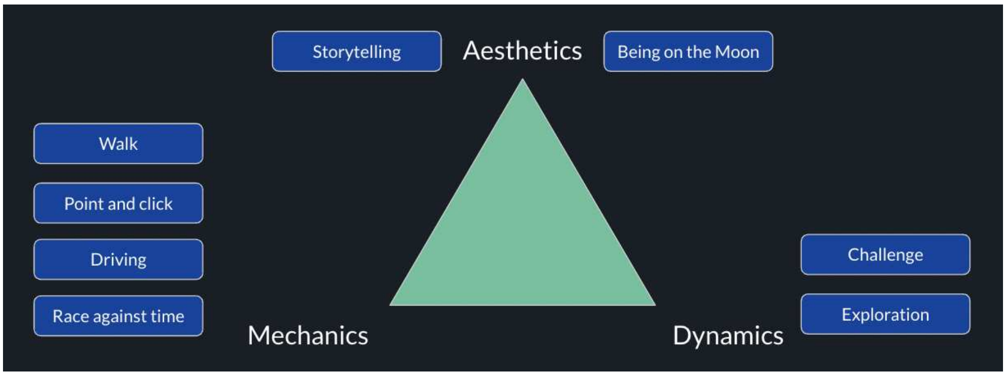
- high level of immersion;
- possibility for interaction;
- adherence to the scientific context;
- comfortable user experience (UX);
- engaging storytelling;
- gamification mechanics;

Table 5.1: Unity elements and functionalities

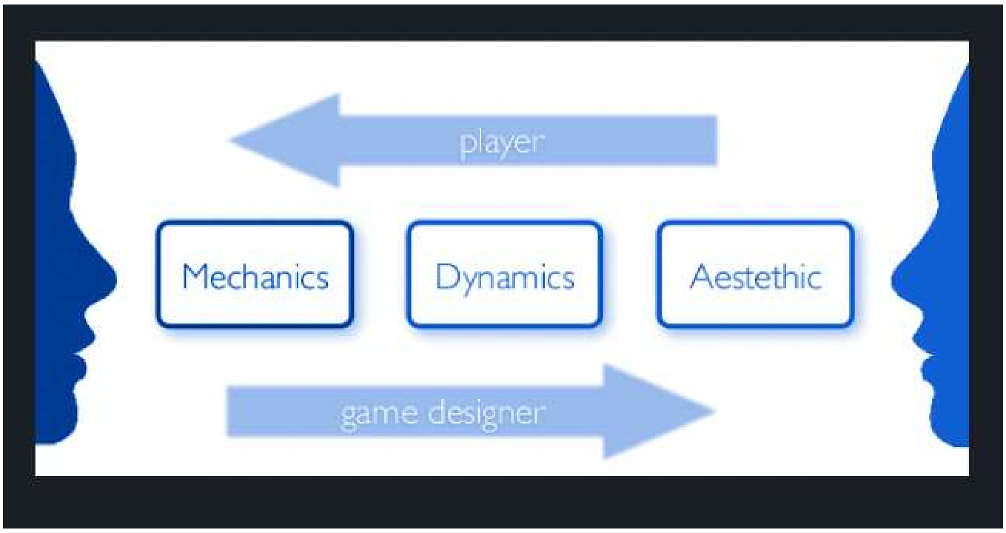
Element	**Description**	**Components/Tools**
3D OBJECT	Simple three-dimensional object populating the virtual world	Transform, Mesh Renderer, Material, Collider, Rigidbody, Script
CAMERA	Object aimed to the rendering of a specific point of view on the scene	Field of view, Projection, Culling Mask, Layers, Clipping Planes, Target Texture
UI	Objects aimed to be interacted by the user	Buttons, TextMesh
XR	Objects aimed to manage extended reality aspects (interaction and movement)	XR Origin, XR Simple Interactable, XR Grab Interactable, Locomotion System
TERRAIN	Three-dimensional editable shape acting as a ground for the virtual world	Paint Terrain, Terrain Details, Terrain Settings
LIGHT	Object illuminating the scene	Type, Shadows
LIGHT SETTINGS	Asset managing the general light settings of the scene	Skybox, Color, Intensity, Diffusion
VISUAL EFFECTS	Series of components adding details and effect to the scene rendering	Particle System

In the following subsections, we will delve into various aspects of the development but will not address the foundational elements mentioned above individually. The reason is that often a single aspect of the virtual experience needs to be designed considering multiple elements simultaneously. In some cases, two or more of the foundational elements were in conflict with each other. The development process also involves finding solutions to these conflicts, seeking creative answers that address all the needs. It is not always possible; sometimes the developer's task is reduced to finding the right compromise between different needs or developing techniques that reduce the specific weight of a problem, even if it cannot be completely eliminated.

In this sense, it can be said that the design and development process of the VR product was outlined through a widely used approach in game design, the *Mechanics-Dynamics-Aesthetics* (MDA) framework (Hunicke, Leblanc, and Zubek, 2004). *Mechanics* constitute the architecture of the experience, the rules govern-



(a)



(b)

Figure 5.3: a) Elements of the MOON RESCUER experience within the MDA framework;
b) MDA framework scheme

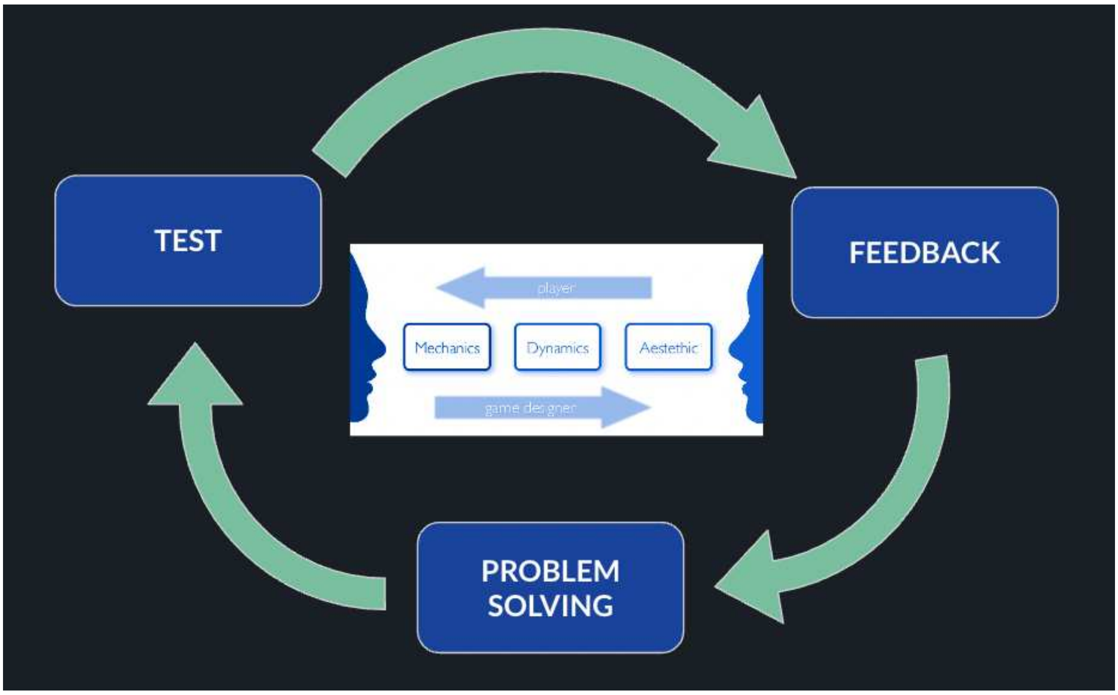


Figure 5.4: Scheme of the refining cycle in game design

ing the objects and their interactions; *Dynamics* is how the user interacts with the mechanics; *Aesthetics* relates to the harmony of the overall experience, including the user: storytelling and UX are elements that contribute to ensuring unity and coherence throughout. Indeed, the design and development of the virtual experience were carried out in an effort to manage the various aspects of the MDA framework (Figure 5.3a). From the developer's perspective, it is easy to focus solely on the mechanics, but since it is an interactive experience, user feedback is crucial, highlighting the importance of dynamics and aesthetics (Figure 5.3b). For this reason, development proceeded through a continuous refining cycle (Figure 5.4). In this context, Beta-testing, which will be discussed in Section 5.4, played a fundamental role in achieving a consistent and effective product.

5.3.1 Input System

A very simple input system already used in many VR applications running on Meta Quest 2 was chosen. The tracking is always of the 6DOF type, although there was a phase during development when the possibility of temporarily disabling rotation tracking in a specific part of the experience (see Subsection 5.3.9) was tested using a script that acted on the CameraTrackedPoseDriver. Regarding active inputs, the two controllers are virtually equivalent: the only button used is the trigger, which implements the *select* interaction.

The Line Renderer generates 3D blue lines, hereafter referred to as *pointers*, to indicate the pointing of the controllers. The interaction range in the virtual space is 30 meters. When pointing at an interactable object within this range, the pointer turns white and the object can be selected. Note that pointing at an object means directing the pointer towards the surface identified by its collider.

5.3.2 Structure and scenes

The first step to prevent the user from feeling disoriented consists in setting up a precise structure. If the experience starts immediately after the running the APK, the user may feel unready and unable to understand what is happening and this easily leads to confusion. Moreover, if the experience is enjoyed during a festival or another kind of public context, the facilitator must have enough time to put the headset on the user's head and give the controllers. Thus, the experience must have a waiting phase that separates the APK running from the actual experience. On the other hand, if the APK is shut down automatically when the experience ends, the user has no time to understand that the experience is over: the general sensation in this case is wondering why the APK terminated. After these considerations, we decided to structure the application of this VR experience along three different phases:

- *Starting* is the first contact for the user with the experience: the first step of the immersion. Our goal is to let the user feel in contact with the environment, completely involved in the new reality that we propose. At the same time, we wanted to avoid the user feeling disoriented so it was crucial to build up a simple scene, with just a few interactable objects and limited movement possibilities. Thus, we created the **Main Menu** scene. That is the scene that is loaded on the device when the APK of the experience is launched. When the scene is loaded, the user winds up in a lunar environment (the Copernicus crater, see Subsection 5.3.3) and is able to take some steps and rotate 360°. Canvas reporting interactable *Start* and *Quit* buttons were added to this scene (Figure 5.6). By selecting *Start* the user enters the second phase of the experience and the *Lunar Landscape* scene is loaded.

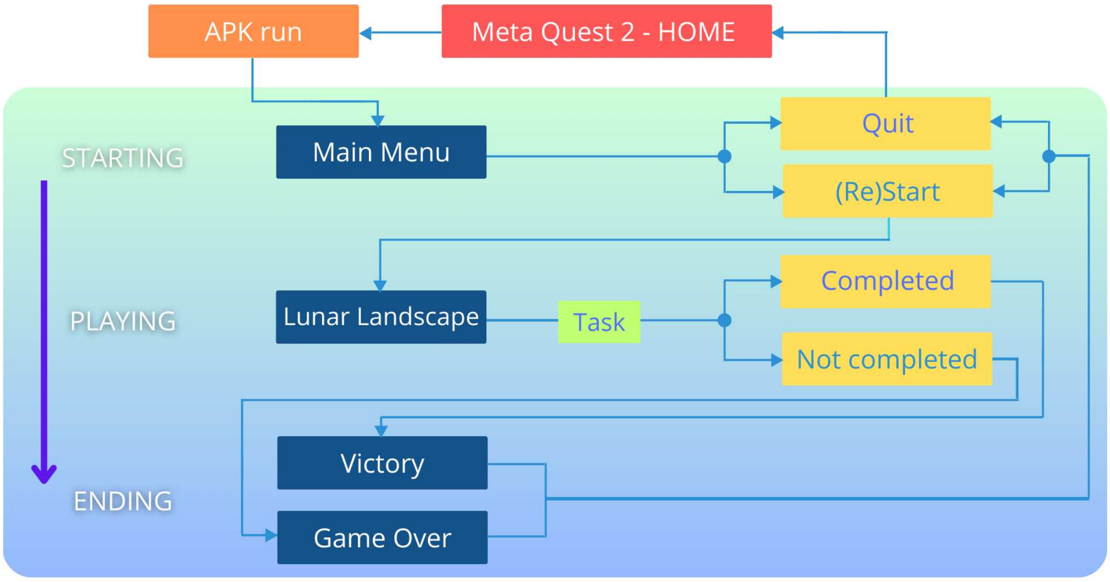


Figure 5.5: This scheme shows the structure of the experience as a simple algorythm. Everything that lies within the green-to-blue box is part of the MOON RESCUER experience.

- *Playing* is the main phase of this experience: the user lives the experience of an astronaut on a future permanent base-camp on the Moon. The set of this phase is the **Lunar Landscape** scene: most of this section will be dedicated to the description of this scene; thus, if not specified differently, we will always refer to this scene in the following descriptions. Later, we will delve deeper into Playing phase, explaining how command training, science contents, and game tasks were arranged within the flow of the storytelling. Due to reasons we are going to explain later, the duration of a part of this phase must be limited by a timer.

- *Ending* is the conclusion of the experience. Two outcomes are possible: **Victory** – if the user completes the proposed task – or **Game Over**. These are also the names of the scenes that are loaded, depending on the actual outcome of the experience. Canvas reporting interactable *Restart* and *Quit* buttons were added to this scene. By selecting *Quit* the user exits the experience and the home page of the device is loaded. The *Restart* button works exactly as the *Start* one in the Starting phase.

Figure 5.5 shows the structure of the experience: the algorithmic representation highlights connections between the user's choices and the different loaded

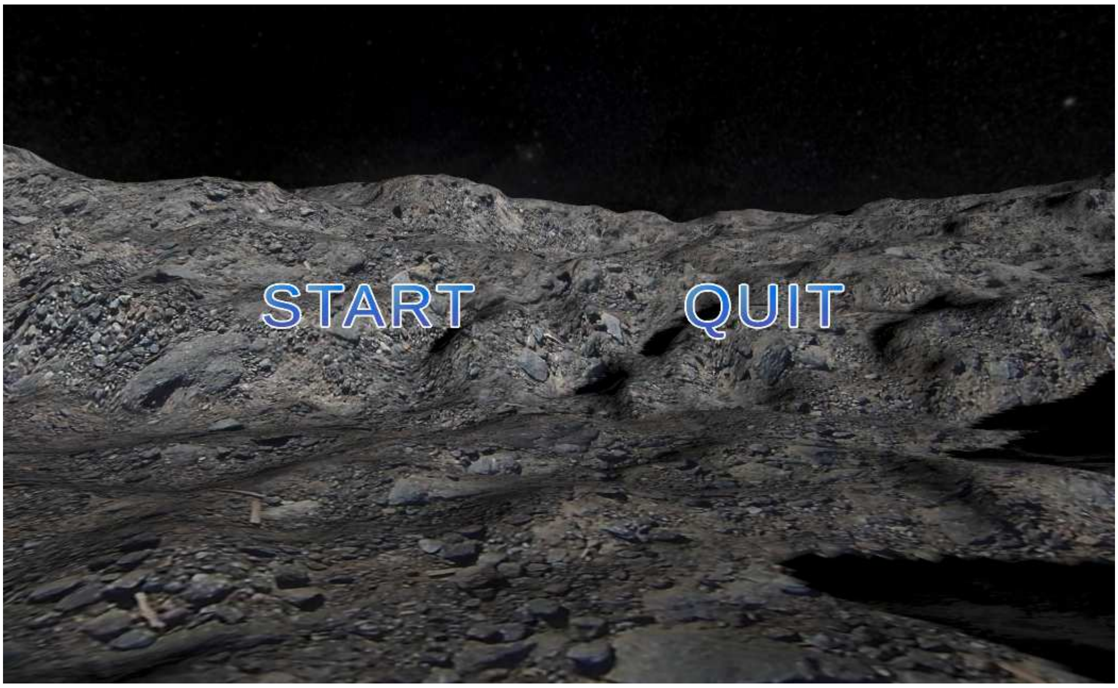


Figure 5.6: User's point of view of the **Main Menu** scene.

scenes. Note that this is just a representation: in the project, there is not a single algorithm managing the succession of the scenes; in every one of the mentioned scenes, instructions about the next scene to be loaded are encoded in script components of the single buttons.

5.3.3 Lunar Environment

Immersion is one of the core aspects of Virtual Reality: users may feel the actual sensation of being within the simulated environment. As a consequence, we decided to set the whole experience on a lunar environment, and in particular on the lunar surface. This looks like a natural choice but it brings a series of issues that must be taken into account during the development of the experience.

First of all, it was necessary to build the environment itself: we needed a ground and a background. As a starting point, we used a lunar landscape scene imported from the Unity Asset Store. This scene (realized by Evgenii Nikolskii, www.artstation.com/evgeny-nikolsky)) includes a 125x125 m^2 Terrain (*Terrain 0*) and a Skybox as background. The Terrain has the shape of a large crater with a deepness of 20 m. Smooth depressions complete the Terrain outside the crater. The Terrain has three different layers of texture representing lunar regolith with different grain sizes. Rocks of different shapes and sizes complete the Terrain as details. Another detail that characterizes this asset is the presence of a particle visual effect to represent the fluctuation of dust grains. Concepually, a detail of this kind would be highly desirable since the presence of floating dust particles actually characterizes the lunar environment. Unfortunately, we had to remove this visual effect from the final version because of its low level of realism. Finally, the Skybox is constituted by a high dynamic range (HDR) picture of the night sky and the whole environment is lighted by diffusion.

The first part of our work consisted of editing this starting asset to increase the realism of the environment. Light settings were modified to reproduce the lack of diffusion and global lighting was substituted with a directional light, obtaining the high contrast shadow effect that is actually found on the Moon. A spherical mesh filter was added to the directional light for the object to look like the Sun. The Sun position was placed on a small angle above the horizon in order to enjoy the shadows cast by the Terrain sides. A lens flare component was added to the Sun to resemble pictures taken from lunar and space missions (Figure 5.8a). A halo was also added to smooth the transition between the light itself and the flare effect. To simulate the Earth, we added a spherical mesh 3D object with a high-resolution Earth map texture and put it far away from the Terrain, scaling the distance and the dimension to resemble the appearence of the Earth when it is observed from the Moon. This solution was tested with different configurations of distance, dimensions, and textures for the spherical object but no suitable configuration was found: it was not possible to get at the same time high-resolution details and atmospheric diffusion evanescence effect. To get a realistic visualization of the Earth, we changed our approach, moving from a 3D to a 2D representation (Figure 5.9): a cut out of the famous *Earthrise* picture – representing the Earth as seen from the Apollo 8 astronauts (Figure 5.7) – was imported as a plain and put at large distance from the Terrain. The resolution of the picture (2400 pixel x 2400 pixel, Credits: NASA) ensured a high level of detail and the distance-dimension scaling was performed without quality loss.

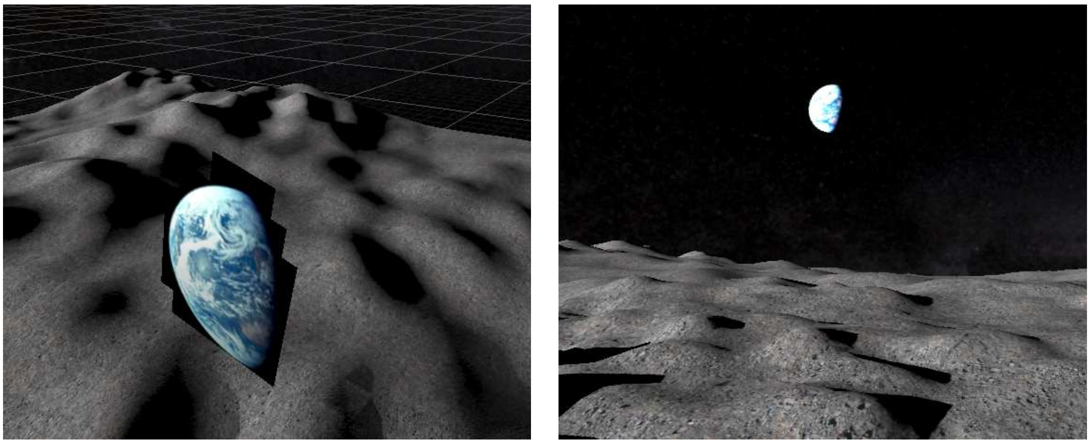
Using a reference frame in which y is the vertical axis, orthogonal to the extension of the Terrain, gravity was set to a value of $g_{Moon} = -1.62 m/s^2$ along the y direction. Since the start of the development, it was clear that some boundaries for the limitation of the accessible virtual space were needed. Differently, users could reach the end of the Terrain and fall in the empty space due to the action of gravity. Limitations were added in the form of invisible walls: four plains orthogonal to the Terrain were added at its edges. Their mesh renderer

Figure 5.7: Earthrise: Apollo 8 mission, 24 Dec. 1968
Credits: NASA

(a) (b)

Figure 5.8: Comparison between a real picture portraying the Sun as seen from the Moon and the virtual simulation.
a)Apollo 14: view from the west of the Lunar Module looking east, 5 Feb. 1971. Credits: NASA
b) User's point of view of the Sun in the lunar sky within the MOON RESCUER experience.

was disabled, while they were equipped with box colliders to constitute a physical barrier to users and object motion. At this point, users were still able to reach the edge of the Terrain: falling in the space was not possible but the realism of the experience was limited by the absence of terrain after a certain boundary. To provide the sensation of having a boundless space in front of them, despite being unable to explore it, we decided to add a second Terrain (*External Terrain*) acting as a far-away landscape. This terrain has 10 times the extension of Terrain 0 and was modeled using the Unity *paint terrain* tool. External Terrain is placed in the same location of Terrain 0, being flat under the lower deep surface of the latter in order to remain invisible for users moving on Terrain 0. The external part was modeled in order to present hills, valleys, and depressions, and only one layer of texture was added. Also, no rocks or other kinds of details were added: this part of the environment is not accessible and the lower the level of detail the lower the cost in terms of rendering. Outer parts of the Terrain were modeled as hills or mountains to give users the sensation that there is never a place - even far away - where the Terrain ends and the space is visible. Figure 5.10 shows a large field overview of the virtual environment as seen in the scene



(a) (b)

Figure 5.9: This figure shows the technique that was used to put in scene the Earth in the lunar sky. In the a) panel it is clearly visible how the object in the scene is a simple cut out of the famous *Earthrise* picture, lowered in exposition. The object as seen from the Terrain is shown in the b) panel: illumination from the Sun provides the correct level of exposition. Despite the low cost in terms of rendering, this 2D approach was more effective from the visual point of view with respect to any 3D representation attempt. Note that the cut out is rotated with respect to the original picture in order to keep the Earth illumination consistent with the position of the Sun in this scene.

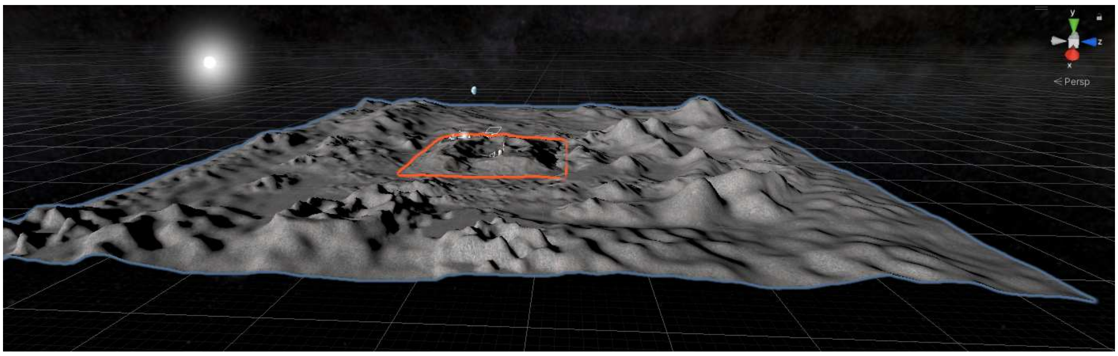


Figure 5.10: Large field overview of the **Lunar Landscape** scene. Orange line: Terrain 0 boundaries, 125 m long per side; Blue line: External Terrain boundaries, 1250 m per side.

window in Unity: the boundaries of Terrain 0 are highlighted in orange while the ones of the External Terrain are highlighted in blue. The Sun and the Earth are also visible in the figure, tens of meters up with respect to the highest level of the terrains.

Digital Terrain Model

During the first stages of the work, we tried to substitute *Terrain 0* with a Terrain that reproduced a real place on the Moon surface. To do this we used a tool to import a Digital Terrain Model (DTM) and use it as a Terrain. In particular, we used Copernicus Crater DTM (Credits: NASA 3D resources). The highest resolution lunar DTM was obtained from LROC WAC stereo image data (Scholten et al., 2012) and they reach a $\sim 100\ \mathrm{m}$ horizontal resolution and a vertical accuracy of $\sim 10\ \mathrm{m}$. This means that such models do not fit the exigence of an immersive environment: terrain features and elevation contrasts have a spatial scale that is not comparable with the scale of the user movements (few meters). Moreover, global dimensions of DTMs are out of the scale of a realistic single exploration (for instance, Copernicus Crater has a radius of $\sim 90\ \mathrm{km}$) and also the processing and rendering of such an extended asset is expensive for the hardware. Obviously, it is possible to downscale the dimension of the Terrain but in this case the search for realism that led to the choice of a DTM would be compromised. Thus, we decided to use a downscale Copernicus Crater DTM only for the Starting (Figure 5.11) and Ending phase scenes, where the user is not supposed to move and the realism is not that crucial. *Terrain 0* was used as the definitive Terrain for the **Lunar Landscape** scene. With this choice, we decided to visually separate the Playing from the other phases.

5.3.4 "One small step... a giant leap"

Movement management is one of the most important aspects of interactive experiences. In the case of VR, it becomes even more crucial since the loss of view of one's own body, the disorientation of moving within an unknown environment and the lack of fluidity in the movements may lead the user to strong confusion, frustration, and discomfort. One of the worst sensations many users feel during VR activities is motion sickness. Most accepted modern theories agree that motion sickness is caused by sensory conflict (Zhang et al., 2016): visual, vestibular, and somatosensory systems may give different feedback about

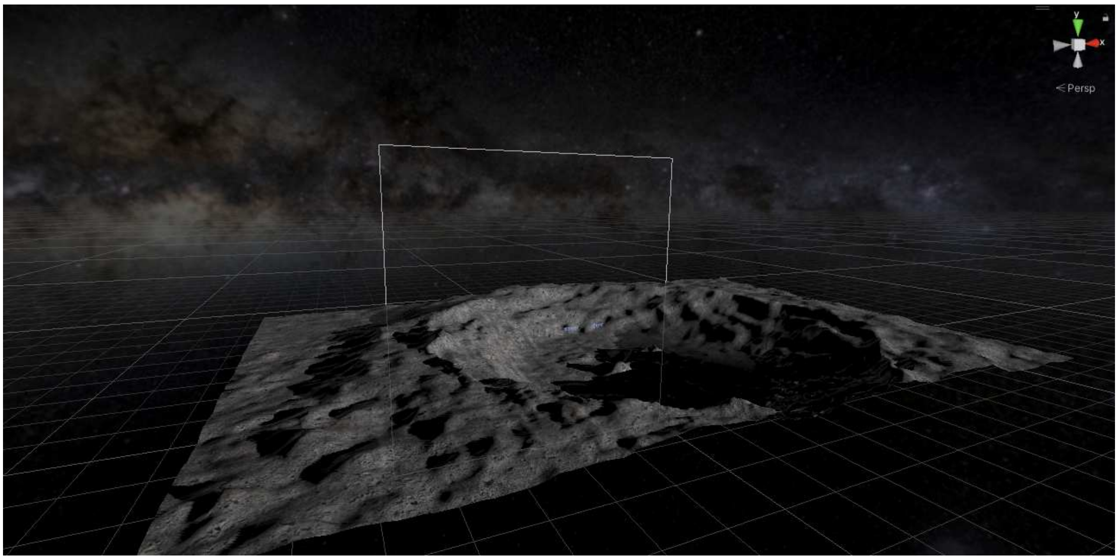


Figure 5.11: Large field overview of the **Main Menu** scene. Copernicus crater DTM is used as Terrain. The canvas with the *Start* and *Quit* buttons is highlighted by a white line

the sensation of motion. In this case, efferent projections reach the temporoparietal cortex, triggering autonomic reactions and also the vomiting center (Koch et al., 2018).

Although some particularly sensitive VR users feel motion sickness just because of disorientation, most of the times this sensation comes up when there is a discrepancy between actual versus expected patterns of vestibular, visual, and kinesthetic inputs (Golding, 2006). Thus, our moving management system was in principle designed to avoid such discrepancy. In Section A.4, we explored the different kinds of motion manageable by the use of a locomotion system in Unity: both snap and continuous turns and also continuous movements generate motion sickness in sensitive people in less than one minute. The problem is that the user feels the whole virtual world moving around, while standing without moving in the real world. This is the origin of the sensory conflict that easily leads to motion sickness. It is a very common problem for many VR experiences: the Mission ISS experience that we mentioned in Chapter 4 (Figure 4.3) uses a locomotion system based on snap turn and teleport (to mimic snap move), resulting in a growing sense of discomfort up to a vomiting stimulus in many sensitive people. Teleport itself does not provide the same negative sensations that snap and continuous movement trigger: because of the instantaneous delay time between teleport active input and location transformation, most users are able to re-set within the virtual environment and the sensory conflict is not generated. Alternatively, it is possible to implement teleport with a broader delay time during which the main camera renders a black screen. This suggests the idea of space and time separation contributing to the prevention of motion sickness. Clearly, teleport constitutes an option for the motion in terms of position, while it does not affect orientation: thus, teleport is not enough for the management of the whole movements in a VR experience, and tracking remains necessary for the orientation management in absence of snap or continuous-turn-based locomotion system. However, using teleport compromises the realism of the experience in terms of sense of presence: in the real world it is not possible to move instantly from one place to another and this would constitute a significant difference from the virtual simulation. The suspension of disbelief sways unless the experience completely engages the user by ilinx-type game techniques (Caillois, Rovatti, and Dossena, 2014). This is not the kind of experience we had in mind so the use of teleportation was avoided from the beginning.

We decided to entrust the whole Player movement to the 6DOF tracking system: all movements that the user performs in the real space are tracked and reproduced in the virtual space. With this choice, we decided to sacrifice realism to foster the user's comfort. In fact, the use of the tracking system automatically excludes the Player from the physics of the virtual world, preventing the reproduction of the jumping motion that we currently associate to astronauts walking on the Moon: if the user jumps, they will fall with Earth-like gravity acceleration in the real space and, due to tracking, also the Player in the virtual space will fall with the same acceleration (Figure 5.12). Therefore, in this experience the user is supposed to move on the Moon surface by walking.

The use of tracking brings another challenge to the realism of the experience. In the real space, the user moves on a flat surface, while the virtual space, in this case *Terrain 0*, is characterized by hills, valleys, and general different slope terrain portions. Since the movement in the virtual space reproduces the one in the real space, the Player does not follow the level of the Terrain while moving, but keeps the same height along the whole movement - the height of the user from the real space ground. The loss of realism connected to such issues remains limited while the Player movements are limited on a small scale: if there are no high elevation contrasts at a low scale in the Terrain, the Player will never look like they are floating over or under the ground. Fortunately, the limited dimensions of the real space prevent the user from performing long-scale walks:

Figure 5.12: Jumping Salute: Astronaut John W. Young, commander of the Apollo 16 lunar landing mission, leaps from the lunar surface as he salutes the United States flag at the Descartes landing site during the first Apollo 16 extravehicular activity. Jumping and falling under lunar gravity conditions is not possible in the MOON RESCUER VR experience. Credits: NASA

some particularly alert users notice that they are moving always on the same level regardless of the Terrain height, but the effect does not impede their sense of immersion within the lunar setting.

Obviously, the exploration aspect would result very downsized for a user actually moving just within a few square meters space. Same for the storytelling: our goal is to involve the user and make them an active part of the story, we do not want to confine it within a small space observing the environment far away. The whole environment must be accessible to the user. To overcome this limit, we found a solution that constitutes a good compromise between the narrative and the user experience aspect: vehicle driving. We are going to discuss the details of this solution in the relative section.

5.3.5 Storytelling: The General Structure

Keeping in mind a general narrative structure was crucial from the initial stages of experience design. Great stories usually include the following phases:

- Prologue
- Crisis
- Climax
- Epilogue

This general structure forms the framework in which all the elements of the virtual experience were built, from scientific content to interaction dynamics: design choices always considered the consistency of the experience within this narrative framework. This narrative coherence of all elements, which falls under the aesthetic harmony that constitutes one of the three poles of the MDA model, deeply enhances the sense of immersion and user engagement. Mental immersion (Section 4.1), in fact, characterizes not only extended reality experiences but also all media where the strength of the narrative can engage the user on an emotional level.

Given the aforementioned structure, it is clear that some aspects of the virtual experience are more suitable for certain phases than others. We will not delve into narrating the entire narrative development here, as this would require mentioning all the elements (scientific, narrative, interactive) that characterize the different phases. However, we will present a series of general principles followed during the development of the individual phases.

Prologue

This phase represents the user's first contact with the virtual experience. The atmosphere must be welcoming, calm, and accommodating, allowing the user to familiarize themselves with the new environment. The objects in the scene should contribute to generating a sense of serenity while also being strongly representative of the narrative context, so the user immediately understands where they are and what to expect. During this phase, we can dedicate a lot of time to describing the environment and the narrative background, providing the user with the necessary elements to contextualize their presence. This is also the ideal phase to provide the first instructions regarding movement and interactions with objects in the virtual environment: a brief tutorial to prepare the user on the use of all commands needed later. For this reason, and to maintain the flow of the narrative, it was decided to structure this phase within the macro-phase of Playing rather than Starting.

Crisis

This is the phase where the equilibrium breaks: something must happen that leads the user to take action. The emotional force of this break is even stronger if it corresponds to a change in environment: in the hero's journey paradigm, following a crisis, the protagonist is forced to embark on a journey to undertake one or more quests.

Thus, it was decided to develop the narrative in such a way that the crisis leads the user to move from the initial, welcoming, calm, and familiar place to a completely unknown location. In this context, the exploration dynamic can be implemented: the user should not be transported to the second environment but should reach it on their own initiative, through a journey that allows them to expand the horizons of their environment.

Climax

This is the phase of maximum tension within a story; it is where the central turning point of the experience unfolds: the resolution of a task. For the goal of this work, the task must relate to one (or more) of the reference scientific contents (5.3.7). In this context, a gamification dynamic can be implemented, so the challenging aspect enhances both emotional involvement and the impact of the scientific content.

Epilogue

The story resolves, positively or negatively depending on whether the user has succeeded in completing the assigned task. Unlike the first phase, this is structured within the macro-phase of Ending: here, it is necessary to prioritize the clarity of the outcome - victory or defeat - over the narrative flow, as the story has now come to an end and the user's attention is solely focused on the result.

5.3.6 Setting

Every story unfolds in a specific time and place (cf. Aristotelian unities). Therefore, the virtual experience must have a precise setting, which must always be considered during development. All the considerations listed below refer to the Playing phase.

The MOON RESCUER experience is set in an unspecified future, at a hypothetical permanent human base on the lunar surface. The base consists of two main stations, named *Monolith Station* and *Moonlife Station*. The user plays as Dr. Clark, an astronaut on her first mission on the lunar surface. After a few minutes of acclimatization, Dr. Clark will face an emergency at Moonlife Station: the outcome of her mission will determine the survival of the station - hence the name of the experience.

For now, we will leave aside the description of the mission and the dynamics of the experience, as the development of these elements is described in Section 5.3.7. Instead, we will focus on describing Monolith Station.

The Monolith Station serves as the starting point of the experience and is located within the main crater of Terrain 0. The object that identifies this place as the heart of the base camp is undoubtedly the *lunar habitat*: the environment that accommodates the daily life of astronauts.

The habitat consists of a cylindrical structure about 5 meters tall, topped by a dome approximately 5 meters high; a horizontal (large) and a vertical (small) tank complement the object along with exhaust pipes and two access staircases. Some three-dimensional details, such as the entry hatch, are handled through

Figure 5.13: Overview of the Monolith Station.

texture mapping. The texture also includes writings and various emblems. This object was not modeled in 3D from scratch but was imported as a prefab asset directly into the scene. The 3D model was retrieved from the NASA 3D Resources repository (https://nasa3d.arc.nasa.gov/). A European Space Agency logo and a European Union flag were added as Text objects directly within the Unity environment: this was because the original texture only included the American flag, whereas this experience aims to suggest that lunar exploration is an endeavor requiring the collaboration of various space agencies.

The Monolith Station is also equipped with a group of six solar panels for energy supply and a radio tower for communications. The 3D models of the panels, the mast, and the radio communication dish were downloaded from Sketchfab, an online platform for sharing 3D models and objects. The objects were imported into Unity as prefab assets; for the radio tower, some material modifications were made to maintain color coherence with the rest of the environment. Figure 5.13 shows an overview of the Monolith Station where all the constituent objects can be seen.

The location was designed to represent a tranquil and welcoming starting point: although it is not possible to enter the habitat, it is automatically perceived as a safe place. This serenity extends to the surrounding space, making it perfect for taking the first steps within the new virtual environment. Not by chance, many exploration-themed video games also feature a starting point associated with the concept of *home*. On the other hand, the surrounding environment is designed to amaze and attract the user to explore. Simply being on the lunar surface has a strong impact: seeing Earth in the distance on one side reinforces the concept of familiarity and, on the other, evokes the sense of wonder commonly associated with space travel. Moreover, being inside a crater automatically stimulates curiosity and the desire to know what lies beyond the visible horizon. All elements contribute to creating a relaxed yet captivating atmosphere that encourages the user to fully enjoy the virtual experience.

The Moonlife Station represents a place where terrestrial life is studied in a lunar environment. In Section 5.3.7, we will describe in more detail the objects that compose it and how they have been utilized. For now, it is sufficient to report that this station is also equipped with a group of solar panels and a communication tower. Additionally, there is a large greenhouse for plant cultivation and a small container that houses a laboratory.

5.3.7 Scientific Contents

In this section, we describe the various types of scientific content that have been incorporated into the experience. To make the reading more fluid, the content is ideally divided into three sectors: lunar environment, technology, and lunar science. In reality, during the development process, the separation between these contents was not so clear-cut: indeed, efforts were made to optimize the design of the various parts of the experience to include many contents without compromising narrative coherence. We will present, for each sector, the different themes, and then dedicate a subsection to each theme, describing how they were integrated into the experience.

One of the main goals of the project is to convey scientific content concerning the lunar environment, particularly the differences compared to the terrestrial environment. In this framework, we are not considering the challenges of future exploration of our satellite; we focus solely on natural features. Thus, our focus is on some natural phenomena that appear immediately different from daily life:

- gravity
- lack of atmosphere

- micro-meteoroids

In addition to the intrinsic characteristics of the lunar environment, another crucial theme that the narrative aims to address is the technological challenges anticipated in future lunar exploration. In this context, the following topics were selected:

- energy provision
- dust collection
- food production

Finally, the last theme we wanted to touch upon was the Moon as a scientific laboratory: the focus was particularly on astrobiology.

Gravity

The gravitational acceleration on the lunar surface is approximately one-sixth of that on Earth: $|\vec{g}_{Moon}| \simeq 1.62\,\mathrm{m/s^2}$. As discussed in Section 5.3.4, it is not possible for the user to directly experience this difference in gravitational acceleration due to tracking constraints. In principle, it would be possible to implement a temporary bypass of tracking through scripting to allow the user to fall with an acceleration corresponding to the lunar one. This solution was explored in the early stages of development but presents several challenges:

- The bypass of tracking should be conditional, dependent on a boolean variable.
- The XR origin would need to have both a Rigidbody component and a Collider.

Temporarily disabling tracking based on a boolean variable results in a very abrupt transition between the two modes - active tracking and inactive tracking - leading to sensory conflicts and motion sickness. Moreover, equipping the XR origin with a Rigidbody and Collider would complicate interactions with nearby objects due to potential collisions and uncontrolled angular momentum. While it might be possible to address this by conditionally enabling Rigidbody and Collider components through scripting, the condition would need to be based on the position of the object in the virtual space. The constant updating of position (the script's update) in the absence of tracking would cause the object to oscillate between having these components active and inactive, preventing it from finding stability.

These considerations were supported by numerous tests conducted during development. Based on these results, it was decided to cease experimentation with the direct experience of reduced gravity effects and to instead focus on interaction with an external object. The idea was to allow the user to throw an object and observe its fall. The most familiar and straightforward object for this purpose is undoubtedly a *ball*.

A 3D spherical object with a diameter of 70 cm and a mass of 0.1 kg was created, equipped with a Rigidbody and Collider, and placed on the ground near the habitat in the Monolith Station. This ball is an XR Grab Interactable object: when the user selects it, it teleports immediately to the base of the pointer and remains attached until the selection button (trigger) is released. The user can thus grab the ball and let it fall from a stationary position by releasing the trigger without moving the arm, or use the tracking of the controller to move the pointer and the attached ball, providing it with some velocity before release. This setup allows for parabolic throws, characterized by a long fall time that further emphasizes the difference between lunar and terrestrial gravity.

Lack of Atmosphere

Thanks to measurements from Apollo surface and orbital instruments starting in 1971, we discovered that the Moon has a tenuous surface-bound atmosphere (Stern, 1999). This exosphere is composed of neutral particles produced from various processes such as solar wind implantation, outgassing, micrometeoroid impacts, radiogenic decay in the lunar subsurface, and subsequent outgassing. Additionally, material is liberated from the regolith by charged particle and photon sputtering, as well as by chemical and thermal release (Stern, 1999).

However, this atmospheric layer is so rarefied that, for practical purposes, the lunar environment can be considered as having no atmosphere. On Earth, we constantly observe the effects of the atmosphere. For example, sunlight is scattered by atmospheric particles, with shorter wavelengths being scattered more (Rayleigh scattering), which gives the sky on Earth its characteristic blue color. On the Moon, the lack of atmospheric scattering makes the sky appear black even during daytime.

(a) (b)

Figure 5.14: User's point of view of the lunar habitat surroundings:
a) streetlamp off: the shadowed zone is completely dark
b) streetlamp on: a part of the shadowed zone is lighted and the ball is visible

In Section 5.3.3, we explained the implementation of these visual characteristics: the virtual experience setting uses an HDR image of the night sky as the Skybox, and all light scattering effects, such as haze and fog, have been disabled by adjusting the settings in the *Lighting* tool.

One of the most striking effects of the lack of atmosphere on the Moon is the presence of sharp shadows. This aspect was alreay mentioned in Section 5.3.3: to achieve realistic shadows in the virtual environment, we chose black for the ambient light color, relying solely on the directional light of the Sun to illuminate the scene. This, combined with the absence of scattering effects, resulted in high-contrast shadows: shadowed areas appear completely black unless illuminated by other light sources.

Accessing shadowed areas is a challenge that astronauts visiting the Moon will have to handle with caution. In the MOON RESCUER experience, this content is presented interactively, allowing users to illuminate a shadowed area by turning on an artificial light. This simple interaction is well-suited, as we will see later, for familiarizing users with pointing and selection commands. The presence of a lamp post in the lunar habitat facilitated the integration of artificial light: a spotlight was placed in the lamp post, with the radius and spot angle set so that the lamp light illuminates a portion of the area in front of the habitat (Figure 5.14).

The intensity of this light is relatively high, only 1.4 times less intense than the sunlight. This ratio should not be misleading: sunlight is a directional light

Figure 5.15: Apollo 15 Commander David Scott performs the hammer-feather drop experiment. Credits: NASA

that illuminates the entire environment with parallel rays, so it does not require exceptionally high intensity. The lamp post light also features a lens flare component, enhancing the contrast between the light being on and off: users expect a light bulb to shine when turned on. In this case, visual familiarity has been prioritized over realism.

The switching of the lamp post light on and off is managed by a script, enabled by the XR Simple Interactable component attached to the lamp post: each time the user selects the lamp post, the script runs, checks the state of the light component, and switches it from off to on or vice versa. To prevent users from having difficulty pointing at and selecting the lamp post, the collider component has been made significantly larger than the physical dimensions of the lamp post.

Another effect of the absence of atmosphere in the lunar environment is observed in the fall of objects. On Earth, the air in the atmosphere affects the fall of bodies in various ways: a falling object displaces a certain amount of gas, which exerts an Archimedean force equal to its weight, $\vec{F}_A = -m_{gas}\vec{g}$; additionally, the friction between the air and a freely falling body produces a damping effect on the fall velocity, $\vec{F}_a = -\beta\vec{v}$, where β depends on the viscosity of the air and the surface area exposed by the body during its fall. These factors explain why we observe objects falling at different speeds on Earth. On the Moon, however, none of these effects occur. A famous demonstration of this is the video taken during the Apollo 15 mission, where astronaut David Scott dropped a hammer and a feather simultaneously, and they hit the lunar surface at the same time (Figure 5.15).

In the MOON RESCUER experience, users have the opportunity to conduct a similar experiment. In addition to the ball mentioned in the previous section, a second, smaller ball has been added, with a radius of 30 cm and a weight of 8 kg, and it is textured to resemble a bowling ball. This *bowling ball* is also an XR Grab Interactable object, which can be grasped and thrown similarly to the previously described ball.

Users can therefore throw a bowling ball and an air-filled balloon simultaneously and observe that both fall with the same acceleration in the lunar environment.

Energy Provision

Energy provision will be a fundamental issue for maintaining a stable base camp on the lunar surface. Palos et al. (2020) state that the traditional method for sustaining space missions - solar panels and batteries - proves inefficient on the Moon due to the large number of batteries required to store energy during the long daytime period (14.77 days).

A more efficient system model, known as Thermal Energy Storage (TES), based on the work of Climent et al. (2014), is presented in Figure 5.16: solar energy is stored in a thermal mass during the daytime and subsequently converted into electricity for use during the nighttime; additionally, the energy required during the daytime is directly derived from the solar source.

Y. Liu et al. (2023) propose an in situ energy storage system based on the use of regolith and a thermoelectric conversion that utilizes the Stirling cycle.

In any case, solar energy collection represents the fundamental approach for the production and storage of in situ energy. For this reason, in the MOON RESCUER experience, several solar panels have been included to visually convey

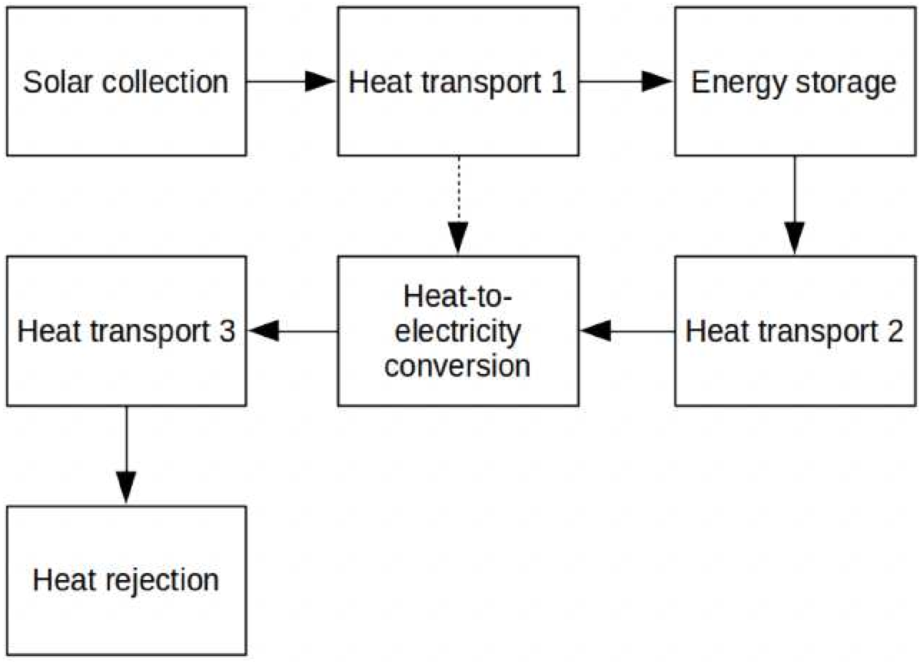


Figure 5.16: Thermal Energy Storage system model by Climent et al. (2014). Credits: Palos et al. (2020)

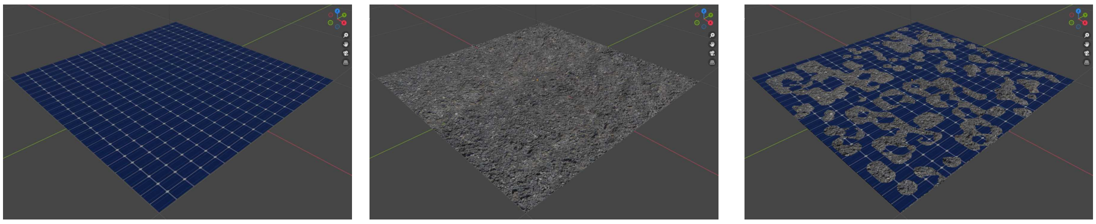
the concept of the centrality of solar energy for future lunar settlements.

As we have seen, the Monolith Station is equipped with a group of six solar panels (Figure 5.13): this group of objects has been duplicated, and its copy has been placed near the Moonlife Station. Unlike the panels at the Monolith Station, those at the Moonlife Station have been made interactive. From the early stages of development, one idea for a task was the maintenance of solar panels. In the next section, we will describe the issue of regolith: in future lunar missions, floating dust particles could likely deposit on the solar panels, compromising their efficiency. Therefore, it was decided to implement a dynamic where the user can clean the solar panels from regolith. Further details of this dynamic will be described in the next subsection. For now, we will explain the measures necessary to make the solar panels interactive and implement their cleaning.

The panels at the Monolith Station are equipped with two materials: one for the base and the outer edge, referred to as *Aluminium* for convenience, and one for the panel surface, called *clean panel*. These materials were already present in the 3D model asset: the *clean panel* material has a texture that reproduces the appearance of solar panels, but its shading remains opaque and lacks the reflective properties characteristic of real panels. Clearly, the panels at the Moonlife Station need to appear dirty due to the regolith, so the material associated with their surface must be different. To create this material, called *dirty panel*, the following technique was used, as shown in Figure 5.17: the texture associated with the *clean panel* material was imported into Blender and applied to a horizontally illuminated plane (Figure 5.17a); a second horizontal plane was overlaid on the first and equipped with the texture associated with a Terrain 0 layer in Unity; finally, this plane with the lunar texture was modified using subdivision tools and proportional editing to create bumps and valleys (Figure 5.17b); in this way, when viewed from above, the overlay of the two planes generates an effect where the panel appears to be covered with raised patches of regolith (Figure 5.17c). This view was photographed from an orthogonal camera to the horizontal plane, and the rendering produced an image, named *dirty panel*, which was used as the texture for the surface of the dirty panels.

The use of this technique, conceptually not very different from texture mapping, allowed for a computationally inexpensive way to create an effect that visually conveys a sense of three-dimensionality.

Creating the *dirty panel* material from the texture is a straightforward operation, whereas it is more complex to give an object the capability to have two



(a) (b) (c)

Figure 5.17: Creation of the *dirty panel* texture process in Blender:
a) horizontal plane with *clean panel* texture;
b) horizontal plane with *Ground 00* lunar texture, proportionally edited in order to have hills and valleys;
c) superposition of a) and b), base for the *dirty panel* texture

interchangeable materials. The reason is that Unity considers the material component of an object (which is computationally an array) as a unique entity, and individual elements cannot be modified via script. Once a panel has a material component with *Aluminium* and *dirty panel* as elements, it is not possible to replace *dirty panel* with *clean panel*. Therefore, equipping the panel with an XR Simple Interactable component and a script that performs the switch between the two materials upon selection was not sufficient to implement the desired transition. The problem was circumvented by creating another object, a duplicate of a single solar panel, called *generic panel*. This object is equipped with three material assets: *Aluminium*, *clean panel*, and *dirty panel*, with the latter two being associated with the surface. This is not an issue, as the mesh renderer is disabled, so the object is not rendered in the scene.

At this point, each of the panels at the Moonlife Station was assigned a script that creates two new material variables - *clean* and *dirty*, both arrays of two elements - and initializes them by copying the values of two elements from the material component of the *generic panel*, resulting in:

$$\text{clean} = \Big(\text{Aluminium}, \text{Clean Panel}\Big)$$

$$\text{dirty} = \Big(\text{Aluminium}, \text{Dirty Panel}\Big)$$

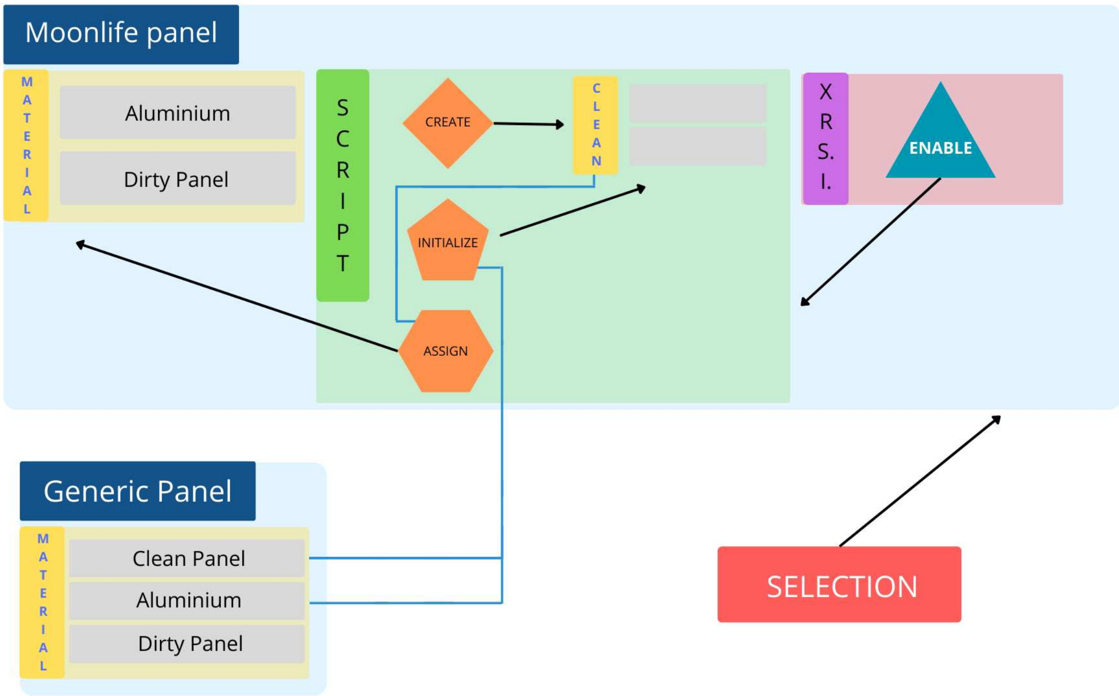


Figure 5.18: Schematic reconstruction of the transition from one material to another for a panel at the Moonlife Station.

At this point, the script can conditionally set the material of the individual panel using a statement that assigns *clean* or *dirty* to the material component: when the dirty panel is selected, the script, enabled by the XR Simple Interactable, assigns the *clean* material, completing the transition from one material to another. Figure 5.18 schematically shows the process from selecting the dirty panel to changing its material.

It is important to note that the operation encoded in the script is not reversible: after the *clean* material is assigned, the script and the XR Simple Interactable are disabled, effectively making it impossible to interact with the panel.

REGOLITH

The issue of regolith was already reported by astronauts during the Apollo missions. regolith presents a range of issues for equipment and structures, such as abrasion of mechanical components and contamination of scientific instruments. Dust grains with average sizes of $100 - 200\,\text{nm}$ - estimated by Park et al. (2008) basing on samples from the Apollo missions (Figure 5.19) - levitate above the lunar surface due to electrostatic forces (Colwell et al., 2009). UV il-

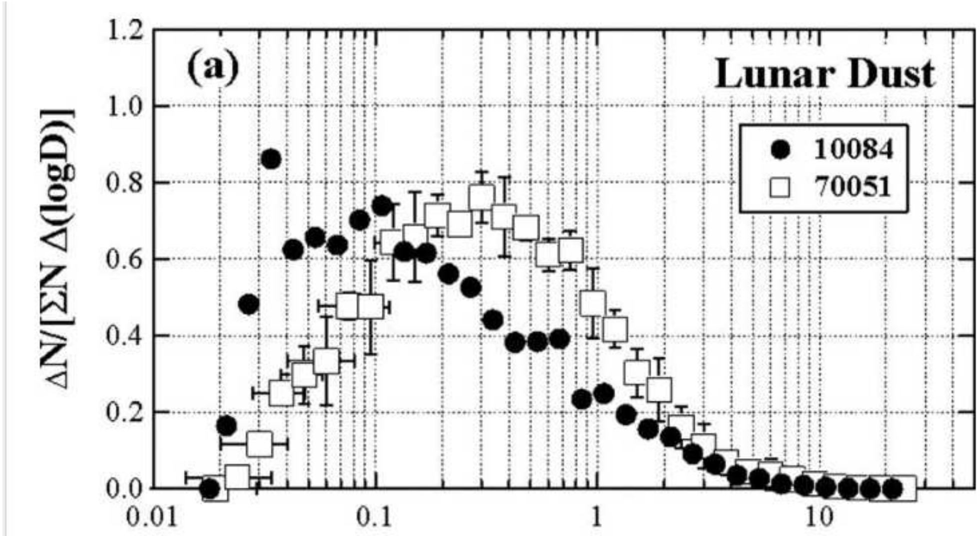


Figure 5.19: Distribution of dust grains diameter for Apollo 11 (dots) and Apollo 17 (squares) samples. Adapted from Park et al. (2008)

lumination and exposure to plasma have been identified as possible triggers for particles charging and jumping to $\simeq 0.1$ m from the surface (X. Wang et al., 2016).

Clearly, it is not feasible to visually reproduce grains that small within the virtual experience, so we chose to represent the dust through particle effects with much larger particle sizes ($\simeq 10$ mm). The phenomena represented are always collective phenomena, but the grain sizes have been increased to make them visually perceptible and appreciable.

We saw in the previous section that one of the tasks proposed to the user involves removing dust deposited on the solar panels of the Moonlife Station. The cleaning of the panels is not only articulated through a sudden change in material but is also characterized by another visual aspect that allows us to focus on the nature of the electrostatic charge of the dust grains. To emphasize the cleaning action of the panels, it was decided to introduce into the experience a representation of a tool that performs dust collection: by selecting the panel to be cleaned, the user will activate this tool, and when it has finished the cleaning, the panel will have changed material. The cleaning tool consists of a suction tube that uses a magnetic field to generate an attractive force towards the charged dust grains (L. A. Taylor and D.-H. Taylor, 2007). Six suction tubes have been created for the six solar panels, and all are connected to a collection structure located several tens of meters away.

Near the panels, the tubes are supported by fork-like structures that keep

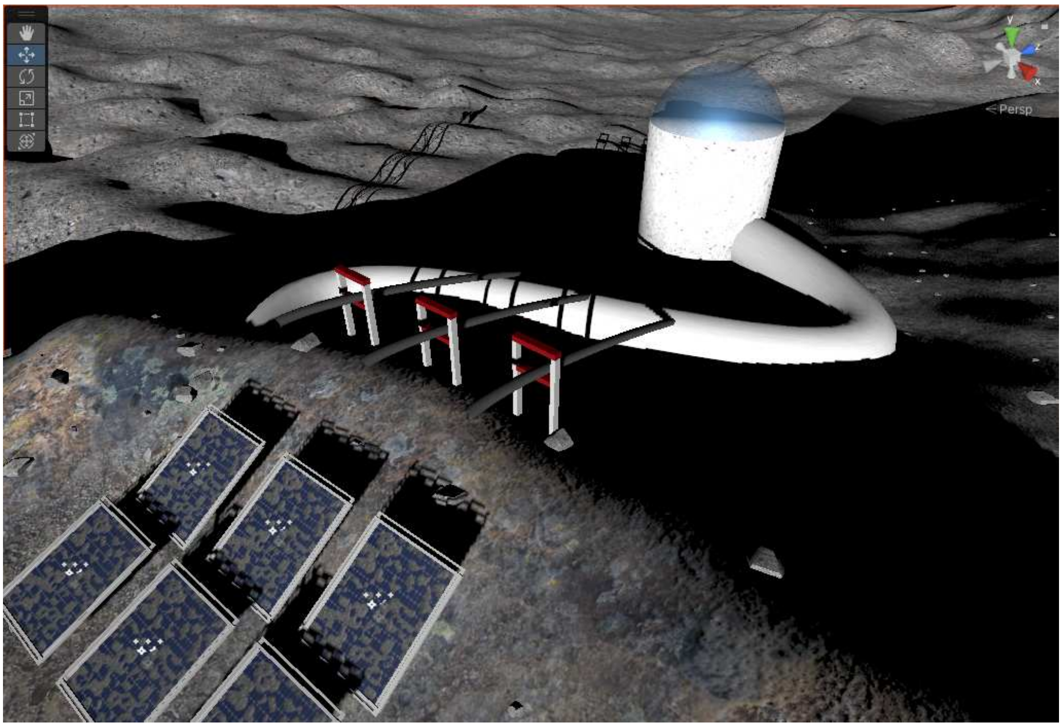


Figure 5.20: Overview of the cleaning structure. Three of the six tubes are visible. Mesh Renderer for the other tubes is enabled when the cleaning process involving them starts.

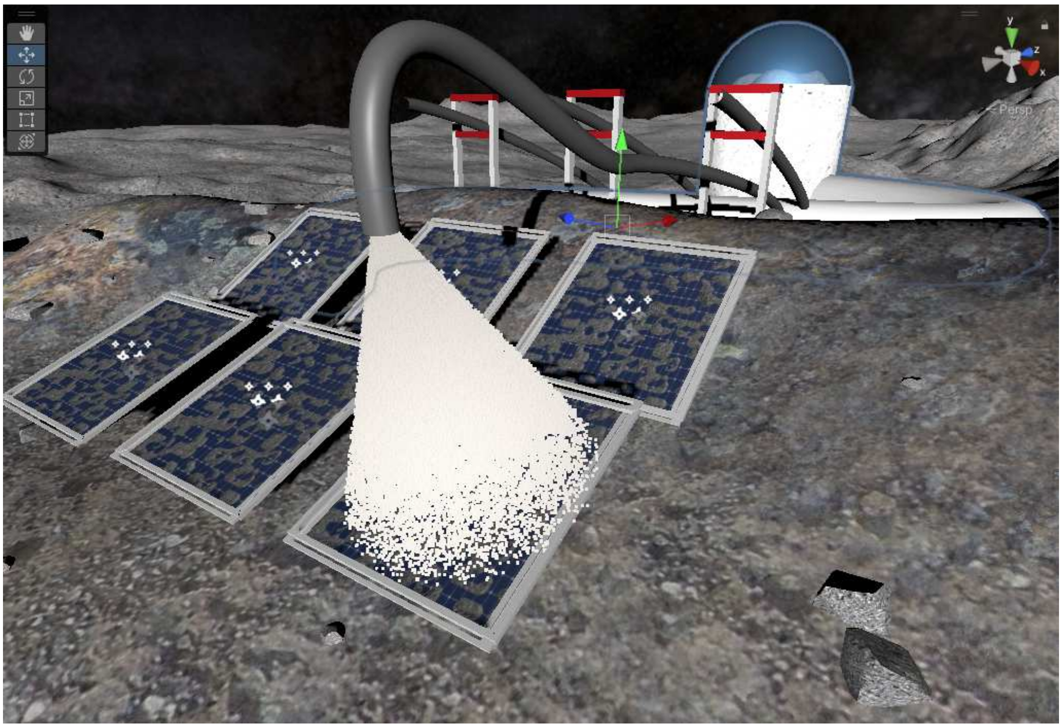


Figure 5.21: Dust collection by magnetic tube. When the particles effect ends, the script that switches the material of the solar panel is enabled.

them separated. The entire setup, shown in Figure 5.20, was modeled from scratch in Blender and subsequently imported as an asset into Unity. When the user selects one of the panels, a script associated with the corresponding cleaning tube is activated. This script enables the mesh renderer for a second section of the tube, which is positioned directly above its reference panel. At this point, the script activates a particle effect: the particles, representing the dust grains, appear at the solar panel and move upwards, forming a cone shape (Figure 5.21). The effect is timed by a timer variable within the script: when the timer reaches zero, no more particles are generated, and the script that changes the material of the solar panel is activated. This effect makes the cleaning of the panel visually more impactful, and the delay time allows the user to better appreciate what is happening.

This is not the only use of particle effects to make the presence of dust tangible in the virtual experience. As mentioned in Section 5.3.3, the **Lunar Landscape** scene originally had a particle effect intended to simulate the presence of floating dust grains. The particle system was removed during development because the visual effect was found to be unrealistic. However, it was still important to somehow retain the presence of dust within the virtual experience. One idea was to associate this content with the concept of body fall in the absence of atmosphere. Footage of the Lunar Roving Vehicle (LRV) guide by astronaut John Young during the Apollo 16 mission clearly shows how the dust behaves when stirred up by the wheels of the moving vehicle (Figure 5.22). As noted in Section 5.3.4, in the MOON RESCUER experience, it is possible to move around by driving a lunar vehicle, although it is different from the LRV, as will be described in Section 5.3.9. To recreate the effect captured in the Apollo 16 mission video, particle system objects were associated with the front and rear wheels of the vehicle. Fine-tuning on size, speed, and emission angle was performed to make the dust particle fall more visible. The result is a very pronounced parabolic trajectory. For the same reasons, it was decided to limit the maximum number of particles in the scene to 10^4 per object. The particles can collide with Terrain 0, but their lifetime is kept short so they disappear from the scene immediately after bouncing. A key aspect is that the wheels generate particles only when the vehicle is moving. To implement this dependency, it was sufficient to include a statement within the *speedometer* script, which calculates the speed of the vehicle.

The statement ensures that the rate-over-time of particle generation is proportional to the speed. From a physical standpoint, there should also be a de-

Figure 5.22: Astronaut John W. Young driving the LRV during the Apollo 16 mission, Apr. 21, 1972. Frame from motion picture film exposed by a 16mm camera. Credits: NASA

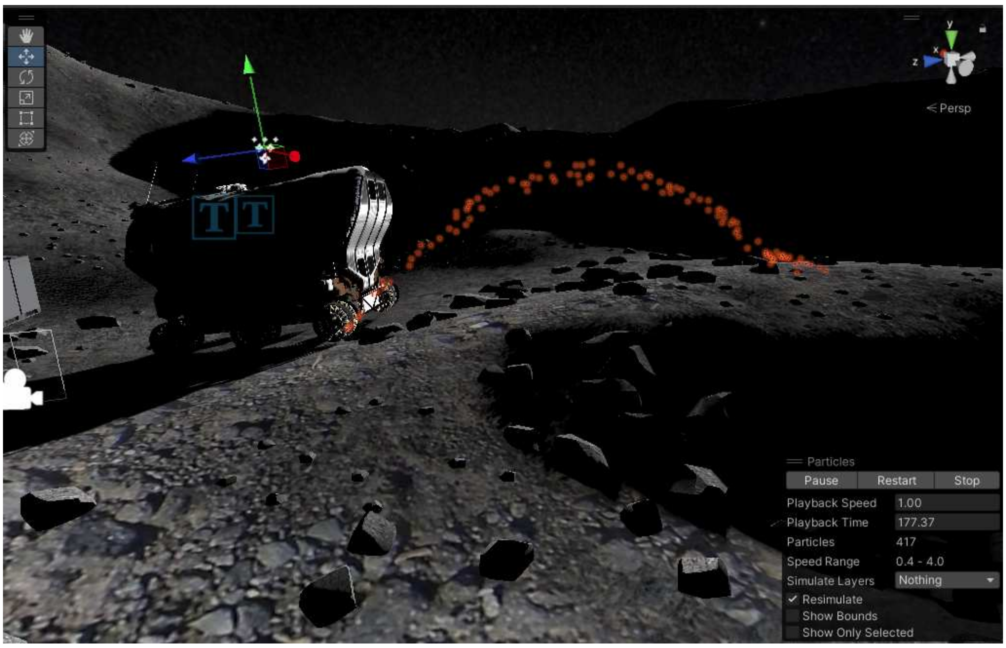


Figure 5.23: Fall of regolith particles due to vehicle motion. Particles are highlighted in orange.

pendency of particle speed on vehicle speed. However, introducing this relationship would have compromised the balance among all components involved in staging the effect: too high speeds would have resulted in fall times exceeding the particle lifetime, while too low speeds would have led to particles unrealistically bouncing on the ground. It was thus decided to ignore this dependency. Figure 5.23 shows the final effect rendering in the development window.

Food Production

Maintaining a stable human settlement on the lunar surface requires a logistical organization capable of meeting the astronauts' needs. A hypothetical lunar base must be self-sufficient in terms of energy and, in general, with respect to resource utilization. Even with the increasing frequency of Earth-Moon travel, the quantity of resources transportable from Earth remains limited. For this reason, all long-term plans for establishing stable settlements on the Moon place crucial importance on the concept of In Situ Resource Utilization (ISRU). Although ISRU is currently discussed primarily in relation to extraction of oxygen and water from regolith (Lavagna et al., 2023) and construction materials for structures (Ferrone, A. Taylor, and Helvajian, 2022), it is evident that, looking further into the future, the in situ production of food resources is also a critical issue for the survival of a human settlement.

We decided to incorporate this theme into the virtual experience by creating from scratch a 3D model of a greenhouse and placing it in the Moonlife Station (Figure 5.24). The greenhouse model was created in Blender, inspired by those depicted in the artistic representation by ESA (Figure 5.25). To represent the glass, a transparent and partially reflective material with a blue tint was used: a completely transparent material is often perceived by users as absent. Inside the greenhouse, there are several plant species: groups of ferns have been placed along the internal perimeter for aesthetic reasons, while for food plants, there is a rice field in the center of the greenhouse and zucchini plants in specific pots placed on shelves near the entrance. A tank and collection containers have been added to complete the setup.

The 3D models of the plants and the tank were modified from free access models downloaded from Sketchfab, while all other models were created from scratch in Blender. Notably, the rice field was created as a standalone Terrain, onto which the rice plant models were added using the tool that adds details to

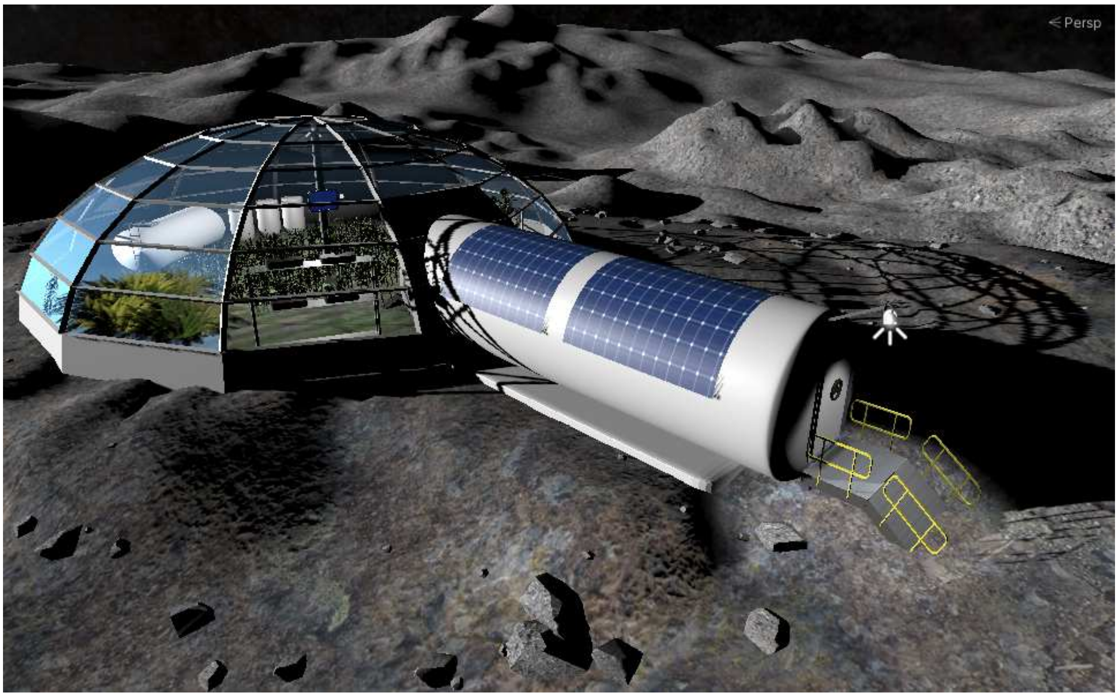


Figure 5.24: Greenhouse in the Moonlife Station.

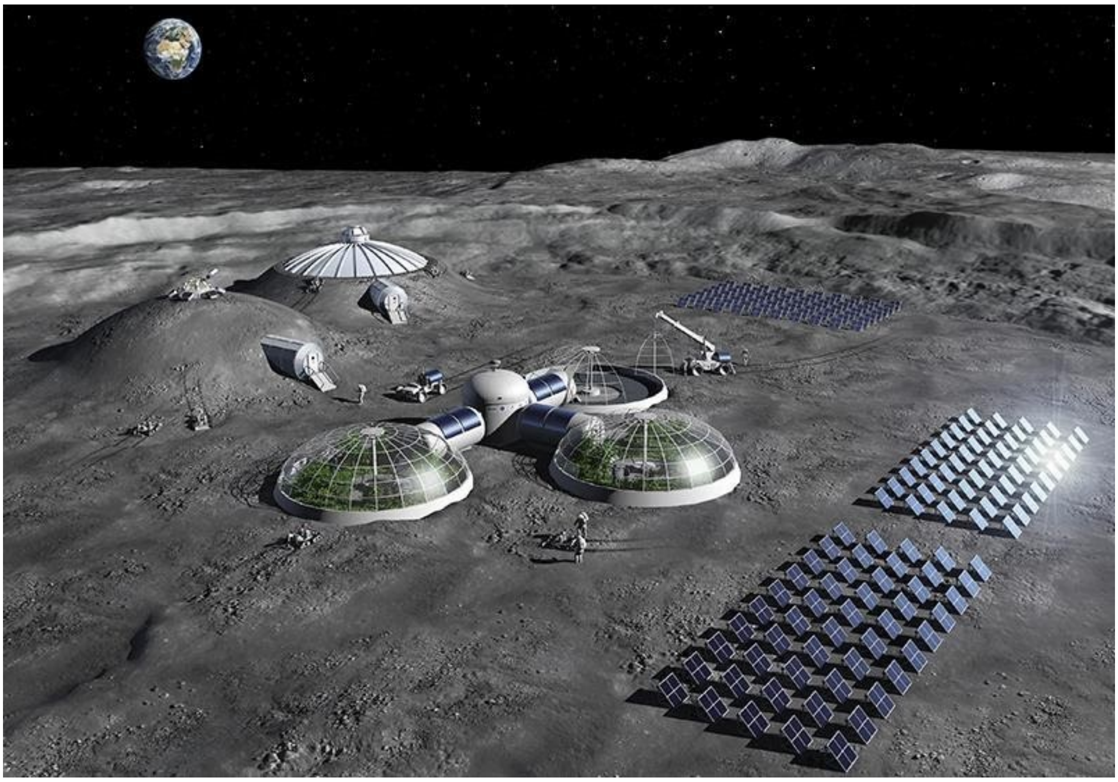


Figure 5.25: Artistic rendering of a lunar base-camp.
Credits: ESA – P. Carril,

the Terrain. A spotlight was added inside the greenhouse: although not strictly necessary, its role is to highlight the details and make the objects inside the greenhouse more visually appealing.

The greenhouse can be accessed through the entrance door, clearly visible in Figure 5.24: the XR Simple Interactable ensures that as soon as the user selects the entrance door, they are automatically teleported inside the greenhouse, slightly beyond the internal door. Similarly, selecting the exit door teleports the user outside the greenhouse.

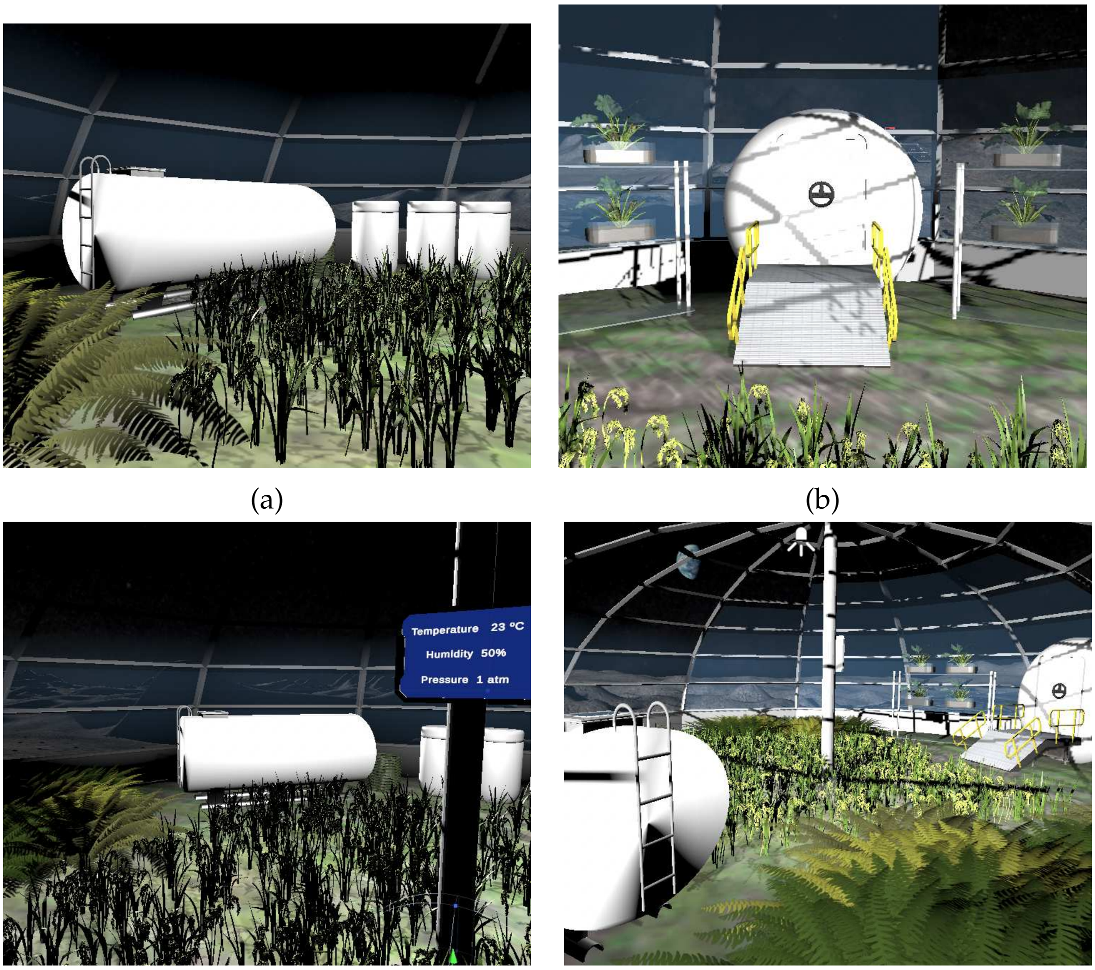
The greenhouse serves as the setting for another task in the experience: the user must repair something that has caused a leak in the greenhouse. The idea is to convey the message that to grow plants in the lunar environment, appropriate conditions must be created: in the absence of conditions provided by the greenhouse, the lunar environment is sterile and entirely unsuitable for life. To illustrate this, a display showing temperature, pressure, and humidity conditions has been placed in the greenhouse: under stable conditions, the temperature is $23°$C, the pressure is 1 atm, and the humidity is at 80%; when the leak is active, these values begin to drop rapidly. The display is equipped with a script that changes the values of the three parameters over time. The storytelling related to the task and its completion will be explained in the next section. Figure 5.26 shows the interior of the greenhouse from various viewpoints.

Micro-meteoroids

The design of a task requires it to be consistently integrated into the storytelling. It was necessary to find something that would justify the problems in the greenhouse. The simplest solution is a breach, a physical damage that jeopardizes the greenhouse insulation. The damage in question is a crack in the glass caused by a meteorite impact.

The Moon is hit by a flux of meteorites with a total mass estimated to be around 1.4 tons per day, showing variations of the order of 10% over a year (Pokorný et al., 2019). These meteorites can originate from various sources - main-belt asteroids, Jupiter-Family comets, Halley-type comets, Oort-Cloud comets - and cover a range of sizes (Pokorný et al., 2019).

The difficulty in visually representing the impact of a medium-sized object from the perspective of an observer on the Moon led us to a simpler approach: not to represent the impact itself but only its effects, namely the physical damage



(a) (b)

(c) (d)

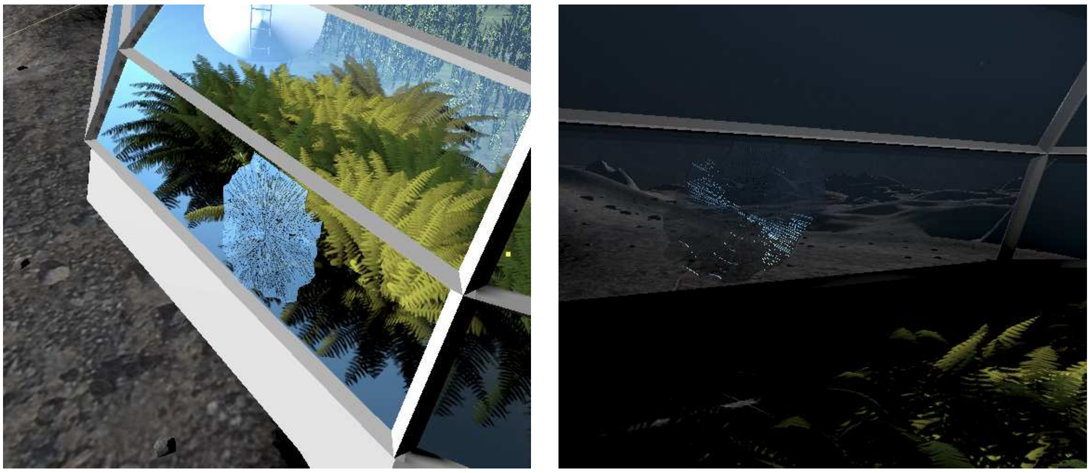
Figure 5.26: Greenhouse inside overview:
a) fern and rice field in close-up, tank and food containers in the background;
b) exit door with plants on its sides;
c) attached to the pole on the right, the display showing the current values of temperature, pressure, and humidity within the greenhouse;
d) large FOV overview to appreciate the positions of the various objects.

caused to the greenhouse. To justify this choice in the narrative, we decided to describe the impact as that caused by a micrometeorite. Cremonese et al. (2013) have shown that the flux of meteorites with sizes of $5-100\mu m$ plays a significant role in the release of neutral sodium in the lunar exosphere. Additionally, several studies have been conducted on the potential damage caused by micrometeorite impacts on a hypothetical human settlement: Allende et al. (2020) studied high-velocity impacts of micrometeorites against Biopolymer-bound Soil Composites (BSC) - a material reflecting the characteristics of possible construction materials derived from regolith. Representing the damage caused by a hypothetical micrometeorite impact thus seems to be a choice that does not undermine scientific consistency, simplifies development work, and supports the storytelling linearly.

In the MOON RESCUER experience, the impact of a micrometeorite generates a crack in the greenhouse, compromising its insulation. The crack has been added as a standalone object on one of the glass panels that make up the greenhouse. The modeling of the crack was done in Blender using techniques that allow generating relatively complex geometry without making the object too heavy for the rendering engine. The 3D object was imported into Unity and assigned the same material used for the greenhouse glass (Figure 5.27). Finally, the crack was given an XR Simple Interactable component to make it interactive: to save the greenhouse, the user must fix the crack using the usual point-and-select mechanism. Once the crack is selected, an attached script disables its Mesh Renderer; the crack disappears from the user's view, the greenhouse glass returns to its intact state, and the task is complete.

5.3.8 Astrobiology

Within the scientific community, there is a widespread belief that the Moon could host promising experiments in the field of astrobiology. The EXPOSE experiments, conducted in low Earth orbit aboard the ISS, have paved the way for the study of life in space environments, and the Moon might represent the next step. de Vera et al. (2012) proposed a lunar landing mission with Raman and PanCam instruments to analyze the lunar surface and survey an astrobiological exposure platform. Such a mission would be able to monitor the stability of life markers in an extraterrestrial environment. According to C. Cockell (2010), long-term laboratory studies on the lunar surface could shed new light on the ef-



(a) (b)

Figure 5.27: Crack in the greenhouse glass:
a) outside view;
b) inside view.

fects of various space environment stresses on organisms. Moreover, Crawford and C. S. Cockell (2010) notes that the lunar environment would be suitable for studies on microorganism survivability at sites of previously crashed and soft-landed spacecraft. Such studies could constitute a starting point for monitoring the spread of biological contaminants outside of human habitats, a crucial aspect for human exploration of the solar system.

To represent the possibility of conducting astrobiology experiments in a lunar base, the MOON RESCUER experience includes the BIOLAB (Figure 5.28). This structure represents a small laboratory where, according to the narrative of the experience, experiments are conducted on various types of organisms and how they react to the particular conditions of the lunar environment.

The BIOLAB was created from a 3D model of a Mars lander, available in the NASA 3D Resources repository (https://nasa3d.arc.nasa.gov/). From a narrative standpoint, it makes sense to think that this structure for studying life in the lunar environment was built before the greenhouse. To suggest this temporal discrepancy, the texture of the model was modified: the BIOLAB has a texture similar to that of the lunar surface, suggesting that the regolith is part of the building material or at least its external covering. While the greenhouse and habitat are imagined to be constructed at a later time, the BIOLAB could be built during the early stages of future exploration, and thus we adhered more closely to current ideas regarding the construction and insulation of structures

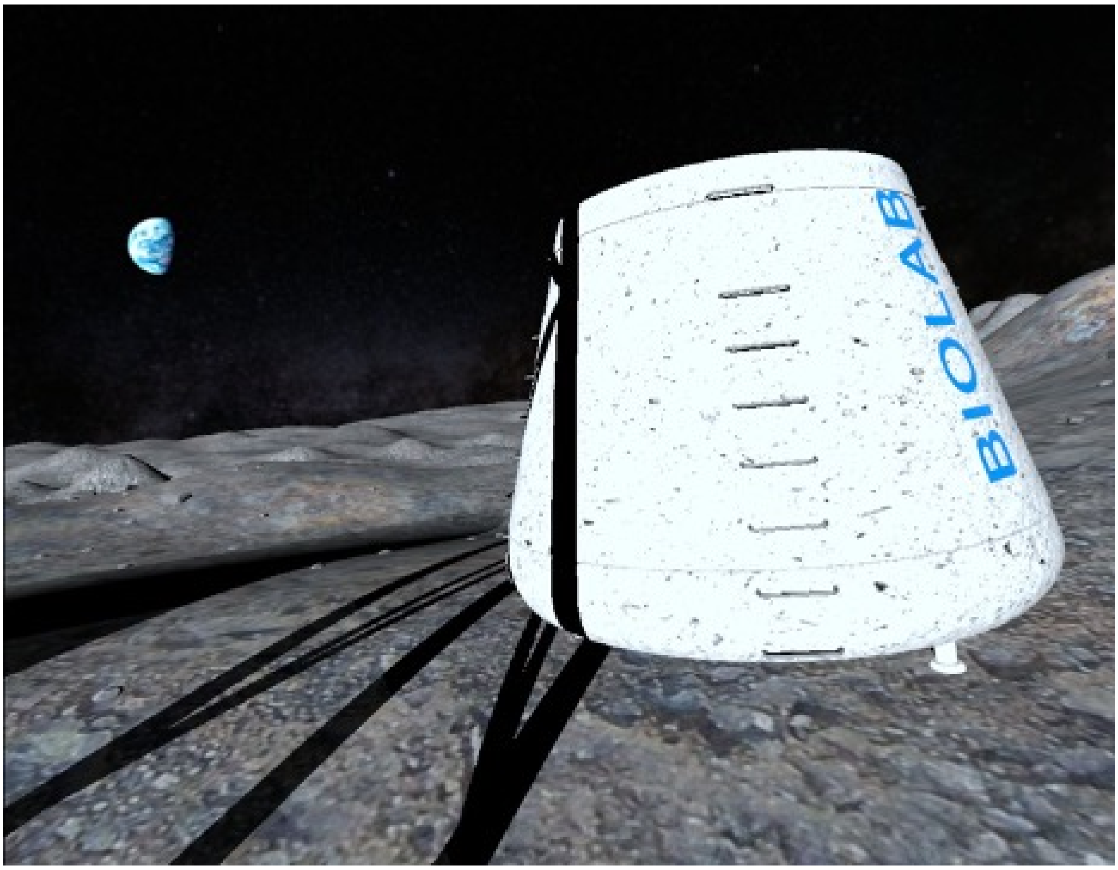


Figure 5.28: User's view of the BIOLAB in the Moonlife Station

on the lunar surface (Ferrone, A. Taylor, and Helvajian, 2022).

Although it is not possible for the user to enter the BIOLAB, it plays a significant narrative role in the task related to cleaning the solar panels. Cleaning the solar panels is necessary to restore the power supply to the BIOLAB. This approach allows, on one hand, the mention of a scientific topic related to biological studies in the lunar environment, and on the other hand, the emphasis on the importance of energy supply in a future lunar base. In this way, it is possible to highlight the critical issue of lunar dust for future permanent human settlements on the Moon: the user does not initially interact directly with the dust but instead encounters the problems caused by its presence. The fact that dust on the solar panels disrupts the BIOLAB power supply, endangering the life of the biological organisms inside, conveys, albeit in a simplified manner, the magnitude of the danger posed by dust to life on the Moon.

5.3.9 Lunar Vehicle

This subsection is dedicated to describing the lunar vehicle. It is undoubtedly the most complex element of the entire virtual environment, and its development has been integral to all other aspects of the experience. The 3D model of the vehicle was downloaded from the NASA 3D Resources repository; before importing it into Unity, it was necessary to modify the 3D object in Blender by removing the window glass, as its default texture was opaque. Modifying the individual material in Unity was not possible because the object is highly complex and rendered using texture mapping techniques. Figure 5.29 shows the *lunar vehicle* object imported into the scene. Regarding physics, the model was equipped with a RigidBody component, with a mass of 500 kg. Various colliders of different types and sizes were added to approximate the complex shape of the vehicle as closely as possible.

The NASA 3D Reosurces lunar vehicle model is characterized by a complete lack of detail regarding its interior. From the earliest stages of development, the idea of the user finding themselves inside a completely empty and dark vehicle seemed to compromise the realism of the virtual immersion and the comfort of the experience. Gradually, new details were added inside the vehicle, some intended for specific functionalities and others serving purely ornamental purposes. We will not delve into the description of each element but will explain later how some of them have been made interactive and functional for the user

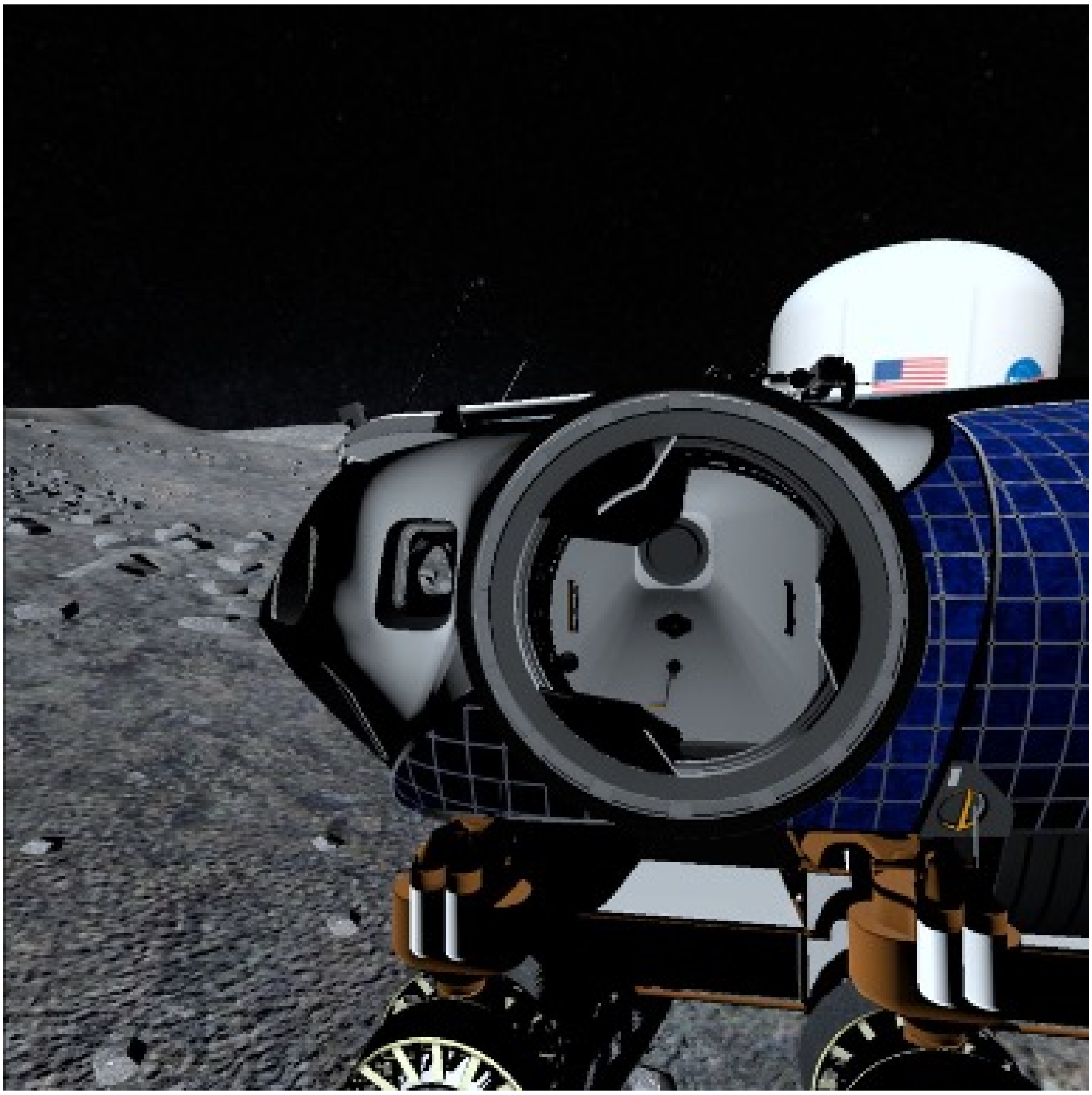


Figure 5.29: Side view of the lunar vehicle.

Figure 5.30: View of the inside of the lunar vehicle.

experience. For example, the internal doors - created by duplicating the external ones in Blender - have an interactive component that is used for exiting the vehicle, as we will discuss in the following subsection.

The general idea was to build a driving station complete with a steering wheel, buttons, and levers. The station is located in the front part of the vehicle, with a display filling the empty space between the windows, while a computer and a laptop flank the control panel on the sides. Lighting is provided by a spotlight positioned above the control panel. The final result of this interior design operation is shown in Figure 5.30.

Beyond its aesthetic representation, the most complex aspects of developing the lunar vehicle are those that make it experienceable from various perspectives. Although these aspects were often developed in parallel, for the sake of clarity, we will present them divided into appropriate subsections.

Entering the vehicle

Creating a comfortable and effective UX for entering the vehicle was one of the most complex challenges in the entire development process. The basic mechanic relies on teleportation: by selecting an XR Simple Interactable object, named *Enter Vehicle*, the user's XR Origin is teleported inside the vehicle. The Enter Vehicle object has no Mesh Renderer component: initially, it was designed as a cubic object with its collider positioned near the antennas on the top of the vehicle. However, after a few tests, it became clear that if the user wanted to enter the vehicle, it would make much more sense to select the door rather than the antennas. The Enter Vehicle was then given a much larger collider and positioned near one of the side doors. To implement the teleportation, a child object named *Teleport* was added to the lunar vehicle. When the Enter Vehicle is selected, its attached script activates, copying the Teleport position and assigning it to the XR Origin.

This solution, however, brought with it a problem that became apparent in the early stages of development. The XR Origin represents the virtual counterpart of the user, but it is not subject to movement tracking: it is the Main Camera object, a child of the XR Origin, that moves in the virtual environment via tracking. When the user physically moves in the real space relative to their original position, the Main Camera object moves relative to the XR Origin in the virtual environment. If the user tries to enter the vehicle after moving far from the position identified by the XR Origin, the relative distance between this and the Main Camera means that when the XR Origin is teleported inside the vehicle, the Main Camera ends up outside. Essentially, the user's position inside the vehicle after selecting Enter Vehicle varies depending on their location at the time of activation. Teleporting the Main Camera directly presented issues due to the CameraTrackedPoseDriver, which constrains the Camera movements to motion tracking.

One of the solutions tested involved disabling the translational component of the CameraTrackedPoseDriver via script: at the moment of Enter Vehicle activation, the position tracking was disabled, and the Main Camera was teleported inside the vehicle. The user could then use rotational tracking to look around, but their position remained fixed. However, this led to motion sickness issues: a user who realizes they can rotate their view will instinctively try to move translationally as well. In the virtual world, this movement is blocked, causing the sensory conflict described in Section 5.3.4. The fact that this sensation disappeared outside the vehicle - translational tracking was re-enabled when the user exited the vehicle - only heightened the sense of disorientation and discomfort when the user was inside the vehicle.

In the final version, we decided to maintain the teleportation of the XR Origin and solve the problem by changing strategy: allowing entry into the vehicle only from a specific position. A child object named *Enter Position* was parented to the vehicle and placed about 1 meter from the left side door. This object has a script component that calculates its distance from the Main Camera during the Update cycle: when this distance falls below a certain threshold ($\approx 0.5m$), the XR Simple Interactable component of the Enter Vehicle object is enabled, allowing the user to select the object and enter the vehicle. Conversely, when the distance between the Main Camera and Enter Position is greater than the specified threshold, the XR Simple Interactable of Enter Vehicle remains inactive, effectively preventing the user from entering the vehicle. This ensures that the user always enters the vehicle from the same point, allowing the position of the Teleport object to be set so that after teleportation, the user actually ends up inside the vehicle.

To make the entry point of the vehicle easily identifiable, we decided to add a cylindrical Mesh Renderer (with a radius of 0.5 m and a height of 100 m) to the Enter Position object, along with a semi-transparent material featuring a light blue texture (Figure 5.31). To the user, this object appears as a beam extending from the sky and pointing to a specific location on the ground. This is a common visual cue in many video games, making it familiar to many users. Clearly, a constant presence of this blue cylinder would compromise the realism of the entire virtual experience. Therefore, the script includes an instruction that enables the Mesh Renderer only when the user is within a certain distance from the vehicle.

The exit from the vehicle was implemented in a similar way: an *Exit Vehicle* object was placed near the internal doors. Its XR Simple Interactable component enables the teleportation of the XR Origin back to the Enter Position location. This way, the entry and exit points coincide.

Driving the Vehicle

Mobility is the crucial aspect of the lunar vehicle object, as it was specifically included to enhance the user's movement capabilities within the virtual world.

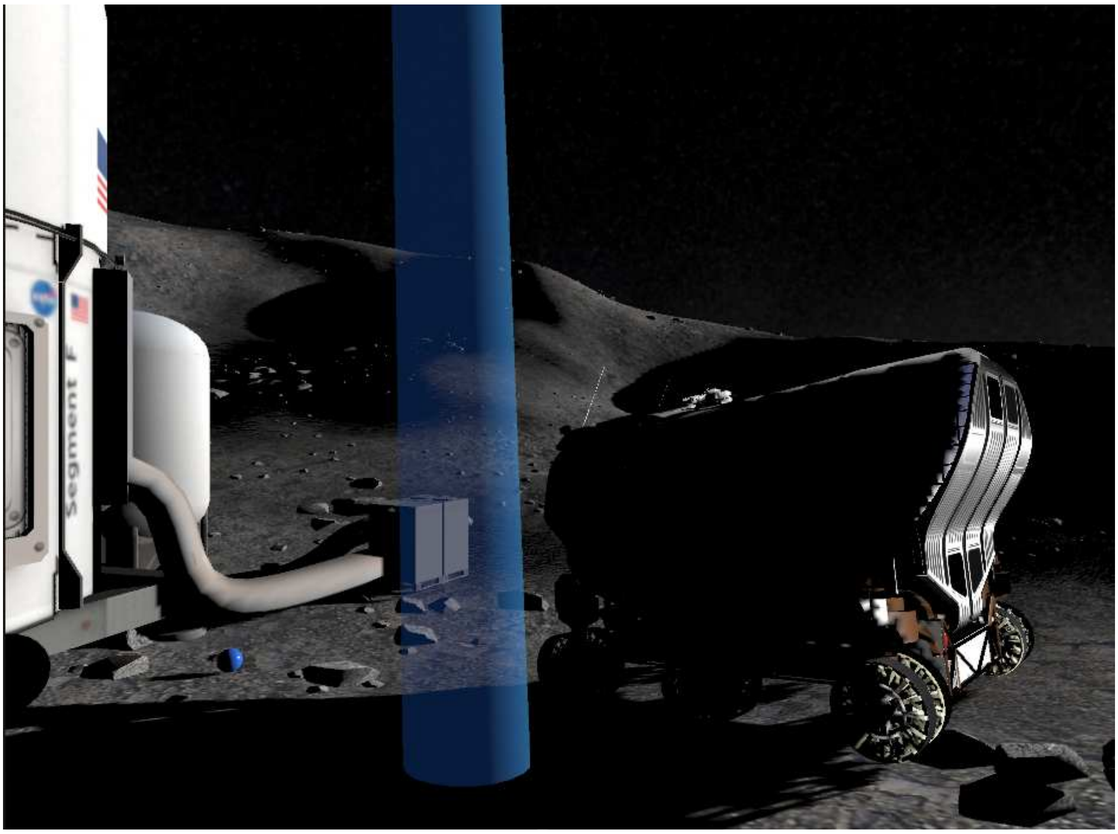


Figure 5.31: User's view of the blue beam indicating Enter Position.

From the early stages of development, it became clear that, unless a very complex automatic movement system was developed, the only viable approach was to implement a driving mechanic using the controllers. The Locomotion System provides all the necessary tools to implement simple and effective vehicle control. To use the Locomotion System, the lunar vehicle was parented to an XR Origin object, named *XR Origin 3* for clarity. A Locomotion System (*Locomotion System 3*) was then parented to the vehicle as a child object, with XR Origin 3 set as the origin parameter. This system implements the Continuous Move Provider, with a speed parameter set to $1\,\mathrm{m/s}$. The provider is enabled only for the Right Hand Move Action, so translational movement is controlled via input from the right controller's joystick.

To enhance the realism of the vehicle movement physics, four *Wheel* objects with wheel colliders were added to the bottom of the vehicle. The two rear wheels were equipped with an independent Locomotion System (*Locomotion System Wheel*), which implements the Continuous Turn Provider, with a speed parameter of $4\,\mathrm{m/s}$. This provider is enabled only for the Left Hand Move Action, so rotational movement is controlled via input from the left controller joystick.

Once the driving system was implemented, it was necessary to temporarily parent the two XR Origins to achieve the effect of transportation: by controlling XR Origin 3, both the lunar vehicle and XR Origin, a child of XR Origin 3, follow its movements. This parenting is temporary, activated through the XR Simple Interactable of Enter Vehicle and deactivated through that of Exit Vehicle. The same applies to the Locomotion System 3 and Locomotion System Wheel components, which are enabled when entering the vehicle and disabled when exiting. This structure ensures that the user can only drive the vehicle from inside it, thus being transported around the environment.

A crucial issue to address is motion sickness. The driving dynamics cause the user to move in the virtual world (transported by the vehicle they are driving) while remaining stationary in the real world. Typically, this sensory conflict between perceived and actual movement triggers motion sickness almost immediately. In the initial stages of developing the driving system, the XR Origin was teleported not inside the vehicle but above it: this allowed the user to see the vehicle moving through the surroundings without having their field of view limited to just the front windows. This is the standard configuration used in most video games that involve vehicle driving. However, with this configuration, motion sickness set in almost immediately: seeing the entire virtual environment move in response to the vehicle commands induced a severe sensory conflict in the user. This is why the configuration was changed to have the user actually enter the vehicle: observing the external world moving only through the windows significantly reduces or even eliminates the onset of motion sickness. This choice also justifies, in hindsight, selecting the 3D model of the lunar vehicle over models of vehicles without a closed command capsule, such as the Lunar Roving Vehicle from the Apollo program (Figure 5.22). The limited perspective, fixed reference points, and the static, accommodating environment inside the vehicle likely reduce the discomfort caused by the movement of the external world. Also, the limited movement speed of the vehicle plays a crucial role. In some tests, attempts were made to increase this value to allow for faster exploration and a wider range of action. The results were unsuccessful: first, driving at high speeds in a rugged environment with unusual gravity often caused the vehicle to overturn; additionally, even slightly higher values than those mentioned, especially for rotational speed, again favored the onset of motion sickness.

Functionality

The lunar vehicle has been equipped with a series of interactive features that enhance its appeal and usability. These functionalities are related to objects located inside the vehicle, and therefore, they can only be appreciated during the driving phase.

In the empty space between the windows at the front of the vehicle, a display has been added that shows the speed at which the vehicle is moving, calculated by a *speedometer*, and the remaining battery level (Figure 5.32). Beyond its ornamental value, this display allows the user to better enjoy the driving experience: the speedometer provides a reference for the user to adjust their driving speed, which is not always intuitive when using joysticks; the *battery indicator* indirectly suggests to the user that they should hurry to reach their destination while driving, helping to keep the experience time from becoming too lengthy. Both the speedometer and the battery indicator are simple Text objects with attached scripts: the former calculates the speed of the vehicle in real-time, while the latter runs a timer that linearly decreases the remaining battery level.

Battery depletion can be accelerated by turning on the headlights. The lunar vehicle model is equipped with eight small headlights located on the roof above the front windows. Since the user may find themselves driving through

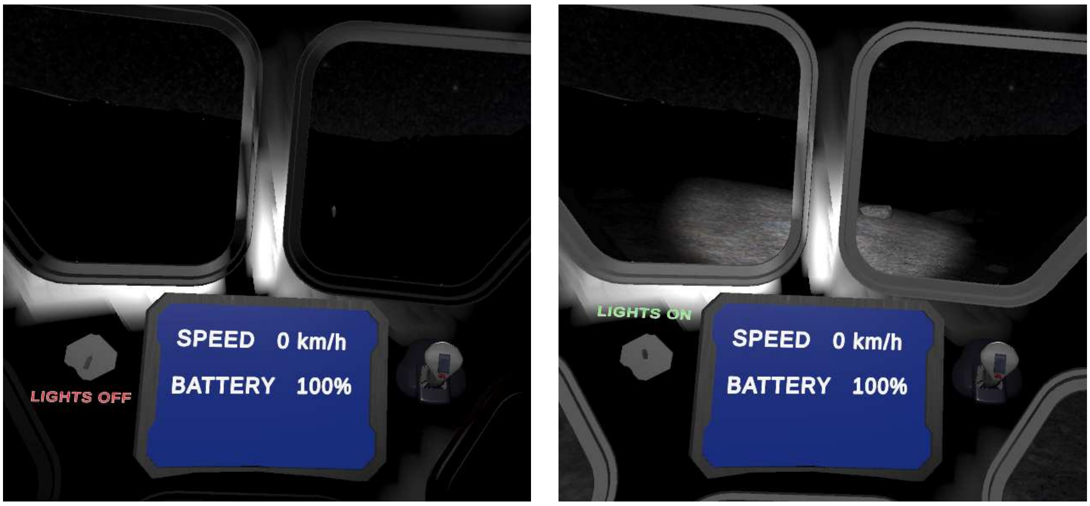


Figure 5.32: This figure shows the details in the front of the cabin:
a) display showing speedometer and battery indicator; light switch off
b) display showing speedometer and battery indicator; light switch on

shadowed areas, it was decided to make these headlights interactive. Four spotlights, aligned parallel to the vehicle, were added to correspond with the headlights. Their activation is managed by an XR Simple Interactable, the *switch*, located near the display mentioned earlier (Figure 5.32). As a 3D object, the switch consists of two cylinders, tilted at opposite angles to each other: depending on whether the switch is on or off, only one of the two Mesh Renderers is enabled. Additionally, two Text objects displaying *Lights On* and *Lights Off* complement the visual aspect of the switch and are rendered alternately. The alternate rendering is controlled by a script, which also adjusts the battery timer by increasing the consumption rate with an additive component when the switch is on. The same script, enabled by the XR Simple Interactable when the switch is selected, controls the headlights turning on and off. The switch has a collider that is relatively large compared to its actual dimensions to facilitate easier targeting.

A final detail concerns the steering wheel: a script updates the steering wheel rotation in real time by mirroring the rotation of the lunar vehicle. When the user attempts to turn the vehicle in a particular direction, they will see the steering wheel rotate in the corresponding direction; this helps the user better orient themselves during turning maneuvers.

5.3.10 Beta-version

We have described all the elements that characterize the MOON RESCUER experience in its initial version. This Beta version has been tested multiple times during and at the end of the development phase. The tests were conducted by people from various audience types, who volunteered to try the virtual experience and provide brief verbal feedback. To organize all the elements described in the previous sections, we present an ordered description of what happens in the experience. Note that in this version, all information and instructions on what to do were provided to the user directly by the developer, who acted as a facilitator.

1. The user starts at the Monolith Station; they receive basic information about the lunar environment and the two bases that make up the scene;

2. The shadow problem is introduced: the user is invited to turn on the habitat lamp; this part serves as a tutorial to instruct the user on how to use the pointing and selection commands;

3. The concept of gravity is introduced: the user is invited to grab and throw the ball; they are then invited to observe how the air-filled ball and the bowling ball fall at the same speed;

4. The user is invited to enter the vehicle;

5. Once inside, the user is instructed on the controls that allow them to drive the vehicle;

6. One minute after entering the vehicle, one of the two tasks becomes active: the user is informed about the nature of the danger and where to go to solve the problem; a five-minute timer starts, displayed to the user via a Text object linked to the Main Camera; the presence of the timer triggers a "race against time" dynamic that enhances engagement and the challenging aspect of the experience.

Depending on the task that is activated - randomly selected from a script - two possible scenarios unfold, which we present in two separate subsections. If the user fails to complete the scenario within the five-minute deadline from the task activation, their mission fails: the **Game Over** scene is loaded.

Scenario A: Power Issues at the BIOLAB

In this scenario, the user is invited to solve the power issue affecting the BIOLAB. The following sequence should occur:

7.A The user arrives near the BIOLAB, at the Moonlife Station;

8.A The user tries to select the BIOLAB: the feedback they receive is access denied, and they are suggested to check the functionality of the solar panels that power the BIOLAB;

9.A By selecting a solar panel, the cleaning process starts, and the problem of dust and the function of the collection tubes are explained; the user is advised to proceed with cleaning all the panels;

10.A The user cleans all the panels;

11.A Victory: the **Victory** scene is loaded, and the user receives congratulations for saving the Moonlife Station.

Scenario B: Crack in the Greenhouse

In this scenario, the user is invited to solve the problem of the crack in the greenhouse. The following sequence should occur:

7.B The user arrives near the greenhouse, at the Moonlife Station;

8.B The user selects the door and enters the greenhouse;

9.B The user is informed about the crack issue: they are told that it resulted from the impact of a micrometeorite and are instructed to find and repair the crack;

10.B The user repairs the crack;

11.B Victory: the **Victory** scene is loaded, and the user receives congratulations for saving the Moonlife Station.

5.4 Beta-Testing

The initial operational tests went hand in hand with various phases of development: it was very important to get feedback from testers on even small aspects of user experience. Some of the choices described in the previous section stem from tests conducted both personally by the developer and through partial tests with people from different audience types. This refining cycle (Figure 5.4) is borrowed from game design techniques and is very effective in identifying issues during development that might be too complex to solve once the product is finalized. A clear example of this is the issue of movement, which we addressed in Section 5.3.4.

In the following subsection, we report some of the feedback obtained during this extensive Beta-testing phase, while the subsequent subsection outlines the adjustments made to the virtual experience following these initial feedbacks.

5.4.1 Beta-test feedback

Each tester who experienced the virtual environment had a very personal interaction with the environment, controls, interactions, and narrative. Some feedback from different users was conflicting, and in some cases, it was unclear how to proceed. Below are some of the aspects highlighted as problematic by many testers, which were then revised using the refining cycle illustrated in Figure 5.4.

1. The **Main Menu** scene appeared a bit sterile and unalluring. As it was the first contact with the virtual environment, users expected something more stimulating.

2. During the lunar vehicle driving phase, many users ended up flipping over. This not only hindered the proper continuation of the experience but also caused a strong sense of discomfort when the vehicle started to move uncontrollably after flipping.

3. Both during driving and generally throughout the experience, many users felt disoriented. Even though they understood how to move, users often did not know where to go, as the placement of objects in the virtual environment was not clear. Specifically, at the task activation moment, most users were unable to autonomously reach the Moonlife Station.

4. Receiving instructions from an external facilitator was very useful to combat disorientation but reduced the immersion in the virtual environment: users still felt connected to the real world and preferred to receive instructions directly within the virtual experience. Moreover, in cases where screen mirroring could not be used, making it possible for the facilitator to see what the tester saw, misunderstandings between the two were frequent and the tester's sense of disorientation worsened.

5. Several users reported that the duration of the experience was excessive. Wearing a headset for a long time can be uncomfortable for some people, and the aforementioned feelings of disorientation contributed to making the experience less pleasant.

5.4.2 Modifications after Beta-testing

We now present the solutions implemented following the feedback obtained from Beta-testing.

1. The **Main Menu** scene was enhanced with an auditory stimulus: a welcoming audio track with tones characteristic of science fiction soundscapes.

The audio file - *Clear Sky*, available for free use on Motion Array - was imported into Unity as an Audio Source object. Additionally, the Start and Quit buttons were made animated, with a script causing them to oscillate back and forth toward the user. An object *box*, using a Sprite Renderer, creates a golden box around the button being pointed at. This combination of multisensory effects greatly increases user engagement and immersion, introducing them to the interactive dynamics of the virtual simulation in a relaxed and welcoming atmosphere.

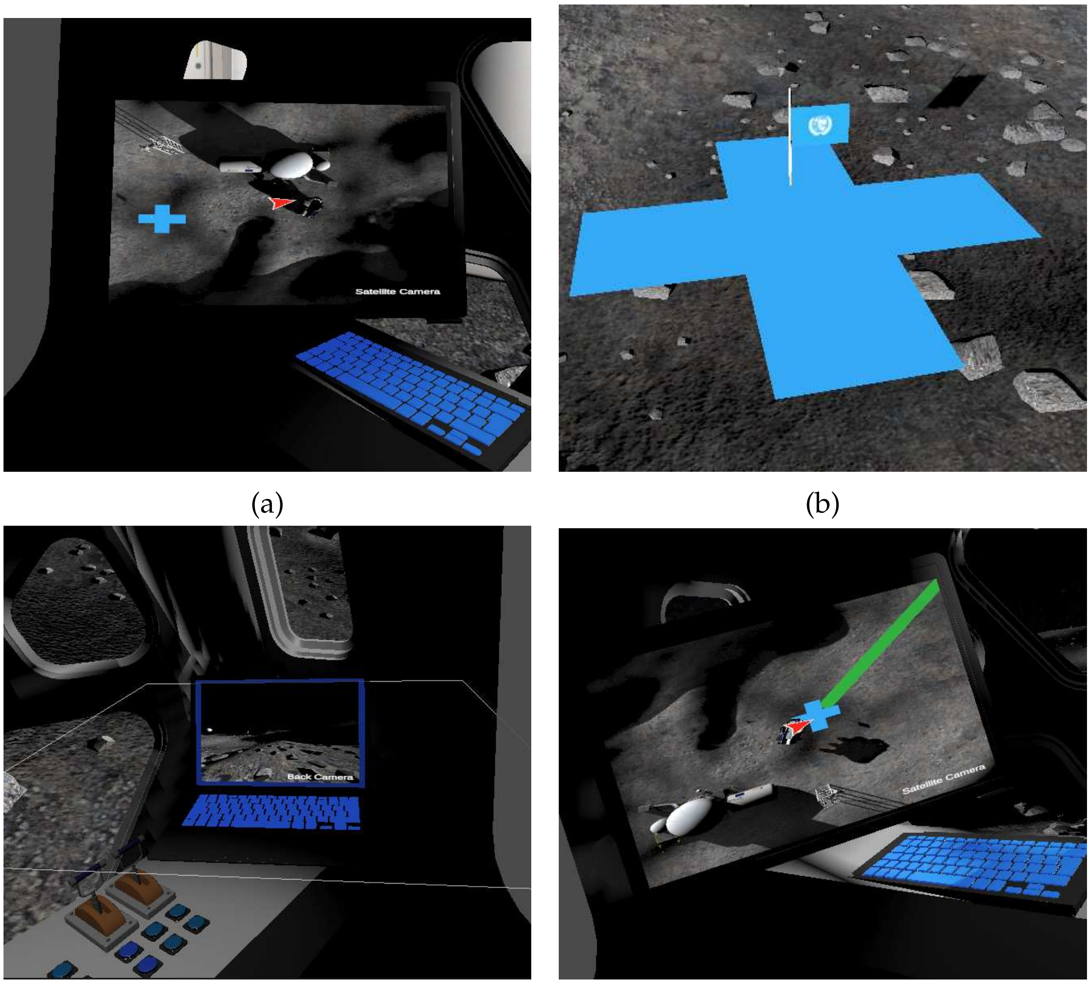
2. The flipping problem was addressed drastically: a script was added to the vehicle that monitors the angular momentum accumulated due to the movements governed by the physics of the virtual environment. When this variable exceeds a certain threshold, the simulation stops and the **Game Over** scene is loaded. The threshold value for angular momentum was established after several tests and fine-tuning with the movement speed values. This solution has a drawback: if the user accumulates too much speed during an ascent or descent, collides with an object, or otherwise accumulates excessive angular momentum while driving, the experience interrupts, possibly before the task is activated. On the other hand, alternative solutions that directly adjust the angular momentum to force it below the threshold to prevent flipping or uncontrolled motion were found impractical. The reason is that the software updates all physical variables of moving objects in the Update method, and any instruction attempting to force a value only has an effect at the moment it is called: the object begins to move continuously, as its angular momentum oscillates between the "natural" value resulting from the physics of the virtual world and the "artificial" value forced by the script. This continuous movement further accelerates the onset of motion sickness in the user.

3. The first adjustment to improve user orientation was to provide a detailed description of the two stations at the beginning of the experience. This description is presented in the first audio file played as the **Lunar Landscape** scene loads (see next point). However, this adjustment was not sufficient. When the user is inside the vehicle, their visibility is limited and navigating becomes complicated for many testers. Following a common approach in many video games, the vehicle was equipped with a system that allows the user to view a real-time map of the region they are in. The map is dis-

played on the monitor placed to the left on the control panel: this panel has a Raw Image component that uses the *Satellite Camera* object as its Image Texture. The Satellite Camera is a camera parented to the Main Camera object, positioned 120 meters above the ground, capturing the scene from above (Figure 5.33a). The Satellite Camera is a child object, so it follows all translations and rotations of the Main Camera: when the user moves with the vehicle, their XR Origin moves, as does the Main Camera; consequently, the Satellite Camera also moves, continuing to view the scene from above and sending what it captures to the Raw Image on the monitor. To facilitate reverse driving, a *Back Camera* was also added, positioned at the rear of the vehicle. Using the same technique, this camera sends its real-time image to the display on the right side of the control panel (Figure 5.33c). The Satellite Camera solution allows the user to better orient themselves relative to their surroundings, but the camera FOV is limited and does not allow both the Monolith Station and the Moonlife Station to be included simultaneously: using a too wide FOV would make the details of the objects less discernible from above and could confuse the user. The presence of the Satellite Camera, however, provides the possibility to give the user a path to follow to reach the task corresponding destination. Two different paths - one for each task - were created using a series of green-textured planes. When the task is activated, the Mesh Renderer of the corresponding path is enabled. The path rendering occurs on a layer visible only to the Satellite Camera, so the path only appears on the monitor (Figure 5.33d). To simplify the implementation of this expedient, it was necessary for both paths to be pre-modeled, each with a well-defined starting and ending point. The starting and ending points were marked with blue Xs, also rendered on the path layer. For convenience, the same starting point was used for both paths. To make the starting point recognizable beyond the map, a 3D object representing the UN flag was imported into its position (Figure 5.33b). Narratively, the flag was chosen for its symbolic value of unity and community for all humankind: a message that space exploration has carried for a long time and that we hope will continue to promote in the future. The event schema described in Subsection 5.3.10 was therefore modified: the task no longer activates automatically one minute after entering the vehicle; after receiving instructions on the necessary vehicle controls, the user is invited to reach the starting point of the task, identified by the blue X; when the user reaches the starting point, the task activates and the experience continues.

4. Providing users with all necessary information within the virtual experience, without any external assistance, represents a significant UX challenge. In this project, it was decided not to provide textual indications, both to preserve the realism of the experience and because multisensory engagement—here ensured by receiving information via audio greatly enhances user involvement. Therefore, it was decided to record the information previously provided live by the facilitator in appropriate audio files. These audio files were uploaded to Unity and assigned to Audio Source objects. Except for the first file, which is played as soon as the **Lunar Landscape** scene is loaded, the activation of the various audio files is managed by scripts attached to objects: for instance, the audio describing the lunar gravity theme and inviting the user to grasp and throw the ball is played only when the lamp is turned on. This sequential organization applies to all audio files: a file is played when the previous step is completed. Naturally, different audio sequences are played depending on the activated task. This solution maintains a high level of immersion and is perfectly consistent with the storytelling: it is not uncommon for astronauts to receive remote instructions via audio. On the other hand, the absence of dialogue between the user and the facilitator may lead to misunderstandings and doubts, especially in the absence of mirroring. However, the facilitator can still supplement the audio instructions when necessary. Depending on the conditions of the experience and the autonomy levels of different users, there will be situations where the facilitator must intervene frequently and others where they can remain more passive.

5. The timer duration has been reduced to 3 minutes. This way, the total duration of the experience rarely exceeds 6-7 minutes. Considering the relatively long path to follow with the vehicle to reach the Moonlife Station, as well as the difficulty some users experienced in reaching the destination within a reasonable time, an *Autopilot* button has been added to the screen inside the vehicle. Once the task is activated, the user can use the Autopilot at any time by pointing to and selecting the button. When the Autopilot is selected, the vehicle, with the user inside, is automatically teleported to the position corresponding to the specific task destination.



(a) (b)

(c) (d)

Figure 5.33: Cameras captures supporting orientation:
a) Monitor showing the live capture of the satellite camera
b) UN flag on the task starting point, in development window
c) Laptop screen showing the live capture of the back camera, in development window
d) The first part of the path to reach the destination of one of the tasks is displayed on the satellite camera live capture.

Clearly, this solution somewhat conflicts with the overall idea of not including teleportation-based movement. However, for most testers, reaching the task destination by driving the vehicle is the most enjoyable and challenging part of the entire experience. For this reason, most users prefer not to use the Autopilot until the time is almost up.

6

Results

After developing the virtual experience, the next step was to present it to users. MOON RESCUER was developed in parallel in two versions: one in Italian and one in English. This allows the experience to be offered in both national and international contexts. To date, the experience has been tested by scientists both in Italy and abroad while tests with public have been conducted only in Italy. In this chapter, we analyze the results obtained from these operational tests. In Section 6.1, we present the feedback obtained from the two types of audiences to whom the experience was offered — the general public and scientists — as well as the feedback recorded by the facilitators who supported users during the experience. We describe the contexts in which MOON RESCUER was presented and provide a detailed analysis of the feedback. The interpretation of test results is a crucial aspect of this project as it offers the opportunity to evaluate both the quality of the work done during development and the effectiveness and challenges of VR technology. In Section 6.2, we discuss the impact of MOON RESCUER as a public engagement product based on the results obtained and the project's objectives. The impact analysis is not limited to quantitative feedback, which suffers from logistical and contextual challenges inherent to a virtual experience like MOON RESCUER, but also considers the results achieved in terms of engagement and communicative effectiveness. The results discussed in this chapter are limited due to the relatively small number of tests conducted and even more so, the limited number of feedback responses received. The data we have provides minimal statistical validity, but new tests in the future may offer additional data to validate and complete the analysis presented below.

6.1 Feedback

The final version of the MOON RESCUER experience was tested with different types of audiences and in various contexts. Kersting, Rolf, and Venville (2021) proposed a conceptual framework for engagement with VR comprising immersion, facilitation, collaboration, and visualization. Based on this framework, we present an analysis of the results obtained from the tests. It is important to specify that the interpretation of the results was carried out by reworking the criteria of Kersting, Rolf, and Venville (2021) in relation to the characteristics of this experience and the goals of this work.

MOON RESCUER is a single-player experience, so it does not offer opportunities for collaboration between users. Therefore, we decided to ignore the evaluation of this aspect within the analysis: collaboration is peculiar in just few VR products, meaning that our analysis keep a very general validity despite this omission.

Immersion and visualization are aspects related to the user's perceptions while experiencing the simulation; thus, it is only through the analysis of user feedback that the effectiveness of MOON RESCUER in these areas can be defined. The analysis of user feedback is covered in subsections 6.1.1 and 6.1.2.

The aspect of facilitation does not concern user impressions but is related to how they are guided and supported during the experience. In most cases where MOON RESCUER was presented, the developer acted as the facilitator. In all other cases, efforts were made to gather the impressions of other facilitators. The analysis of these impressions is discussed in Subsection 6.1.3.

MOON RESCUER was presented to both the general public and members of the scientific community. Obtaining feedback from both sides is crucial to understanding whether this type of product can strengthen the relationship between the public and the scientific world. Additionally, expert opinions on the scientific accuracy of the product and its effectiveness in terms of communication are very important for the goals of this project. Regarding the collection of user feedback, post-experience questionnaires were used. We developed two different questionnaires: one for the general public and one for the scientific community.

6.1.1 Public feedback

The questionnaire for the general public was developed first. The idea was to expand the concept of *immersion* as reported by Kersting, Rolf, and Venville (2021) and evaluate the virtual experience under different aspects:

- immersion
- engagement
- scientific contents transfer (SCT)

By immersion, we mean the experience ability to immerse the user in the lunar environment, temporarily separating them from the real world and generating a strong suspension of disbelief (4.1). The realism of the reproduction and the comfort of interactions with the environment are among the key parameters in this regard.

Engagement refers to the emotional impact of the experience on the user. User involvement and positive reactions are the reference parameters in this case.

Regarding scientific contents, given the structure of the experience, some aspects are more central than others: the user spends a significant portion of their time experimenting with lunar gravity, while the aspect of micrometeoroids is only briefly mentioned in the storytelling. This also allows us to understand how making content experienceable and interactive impacts the ease of its transfer. On the other hand, some contents may have been received more than others; therefore, it was important to include an open-ended question in the questionnaire about the scientific contents appreciated by the user, in order not to influence the responses.

The questionnaire administered to the public is presented in Table 6.1. The questionnaire includes multiple-choice and open-ended questions. There are questions that address each of the three aspects mentioned above. Additionally, some questions were included to profile the users, in order to better contextualize their responses to the questionnaire.

MOON RESCUER was presented to the public mainly in two contexts: SPARKme in Matera and the Department of Geosciences at the University of Padua. SPARKme is a visitor center focused on space exploration. The center hosted the first public

Table 6.1: Questionnaire for the public

Aspect	Question	Kind of answer
Engagement	Did you enjoy the VR experience?	Multiple choice
Profiling	Did you ever test a virtual reality experience before?	Multiple choice
Immersion	How did you feel movements and interactions within the virtual environment (comfort and realism)?	Multiple choice
SCT	Did this experience increase or modify your knowledge about the Moon?	Multiple choice
Engagement	How did you feel within the virtual environment?	Open
SCT	Which scientific aspects did you experiment within the virtual environment? How did the experience allow you to do it?	Open
Profiling	How old are you? What is your job?	Open

tests of MOON RESCUER. The experience was integrated among the various attractions of the center: a $4m$ diameter polycarbonate dome was reserved for the user wearing the headset, while a 50-inch screen outside the dome was used for mirroring, allowing others to observe what the user was seeing inside MOON RESCUER. Clearly, this context did not allow for the selection of a single category of audience, as all visitors to the center could experience the virtual tour as part of their visit. However, since the visitor center frequently collaborates with schools, the visitor base also included the primary target audience for MOON RESCUER.
The Department of Geosciences at the University of Padua hosted the experience in its VR lab. A group of students had the opportunity to engage with the experience as part of a university course that explores the use of virtual reality for scientific purposes. In this context, the availability of several Meta Quest 2 devices allowed multiple students to enjoy the experience simultaneously, enabling us to reach a good number of users in a relatively short time. In this case, the audience was more strictly selected. Combining the interviews conducted with testers in both contexts, 34 feedback responses were collected.

The scatter plot in Figure 6.1 shows the users' prior experience with VR in relation to their age. The graph clearly indicates that most testers fall within the age range that represents the primary target audience of MOON RESCUER. We

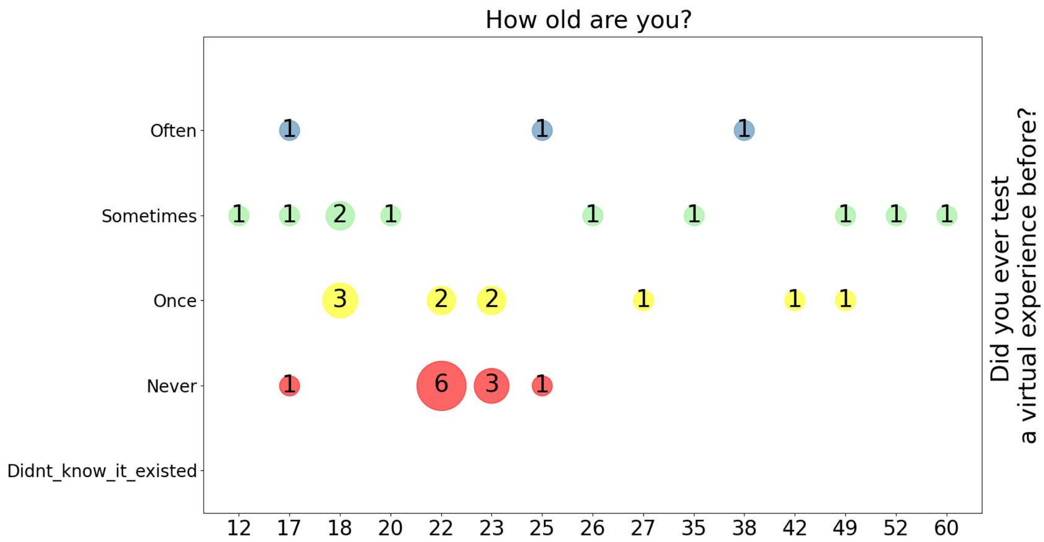


Figure 6.1: **Public** - Profiling scatter plot: experience with VR vs age. The dimensions of the spots represent the frequency of the related couple of answers, reported also by the numbers inside the spots.

also note that, despite their young age, many testers have low familiarity with VR technology. These profiling considerations confirm that this technology can be very appealing to the target audience, but they also suggest that this attraction does not always accompany actual user experience.

This indicates that, for the analysis of the results, it makes sense to examine the feedback as a whole, without making a priori distinctions based on profiling. In hindsight, we can say that there are no significant differences in the feedback when examining the complete sample or selecting only the target audience. The only exception to this is related to the perceived value of the experience from the perspective of scientific concepts, which we will address later.

The feedback results indicate that MOON RESCUER ensures a good level of engagement: over 88% of respondents expressed positive opinions about the virtual experience, and more than 41% reported the highest level of satisfaction (Figure 6.2). Positive feelings also emerge from the analysis of the responses to the open-ended question about how users felt in the lunar environment. Most users reported feeling comfortable. In Table 6.2 we present some particularly significant responses from members of our primary audience. These responses show how the experience had a significant emotional impact, successfully captivating users and transporting them to the surface of the Moon. The level of

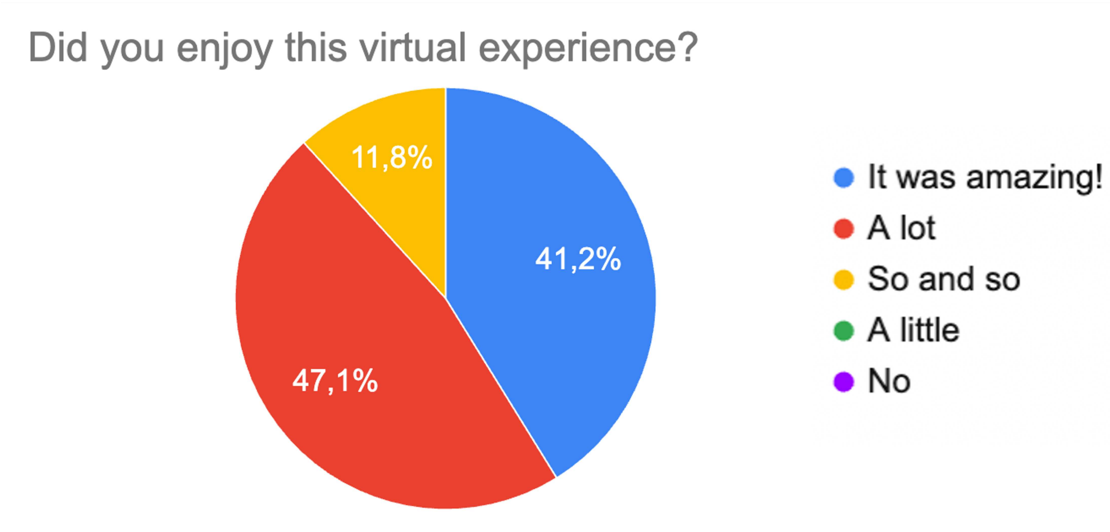


Figure 6.2: **Public** - Pie chart for the question regarding a general opinion about MOON RESCUER.

engagement is confirmed to be very high, and users expressed satisfaction with the realism of the environment depicted. Some people reported a bit of disorientation, but despite this, the experience was never unpleasant for anyone.

Table 6.2: How did you feel within the lunar environment?

Answer	**Age**
Like I was on the moon. Or like I was in another environment	26
At ease, as I was part of the environment	18
Inspired and never disoriented	23
I was an amazing experience, close to reality!	22
A bit disoriented but intrigued by the new environment	17
Confused little bit	22

Some of the responses obtained from this open-ended question suggest that the level of immersion was also generally appreciated by the users. More than 82% of respondents expressed positive opinions regarding the comfort and realism of movements and interactions with the environment (Figure 6.3). On the one hand, we see that about 20% of respondents consider the experience excellent from this perspective; on the other hand, it is important to note that a non-negligible percentage of users - almost 15% - believe these aspects could be improved.

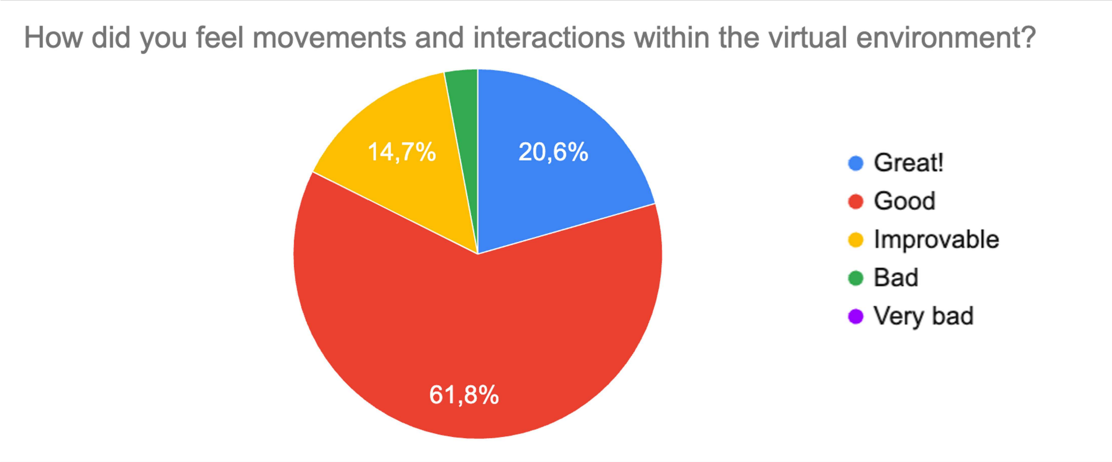


Figure 6.3: **Public** - Pie chart for the question regarding comfort and realism of movements and interaction.

Regarding the effectiveness of the experience in terms of communicating scientific content, we see that the feedback is relatively positive: over 70% of users stated that they learned something new about the Moon or modified some of their previous knowledge (Figure 6.4). On the other hand, one in four people reported that they felt little or not at all enriched by the scientific content of the experience. The scatter plot in Figure 6.5 shows that geology students were the ones who provided the most critical feedback in this regard. It is likely that the scientific content offered by MOON RESCUER is not particularly educational for university students, whose level of knowledge, although in a different field, is certainly higher. The other respondents, whether students or not, generally felt that they gained new scientific knowledge from the experience.

Analyzing the responses to the open-ended question about the scientific concepts learned through MOON RESCUER, we find that gravity and the absence of an atmosphere are the concepts most commonly mentioned by respondents. Figure 6.6 was created by identifying the concepts mentioned in the responses. We see that almost all the scientific content included in the experience is represented in the responses, although most of them are mentioned by only one or two users. The themes of gravity and the lack of atmosphere are relatively universal.

On one hand, this suggests that the first part of the experience is particularly instructive: the user performs simple actions, similar to those they might do in their daily life, but by doing them on the Moon, they manage to learn something new about this environment. On the other hand, contents presented within the

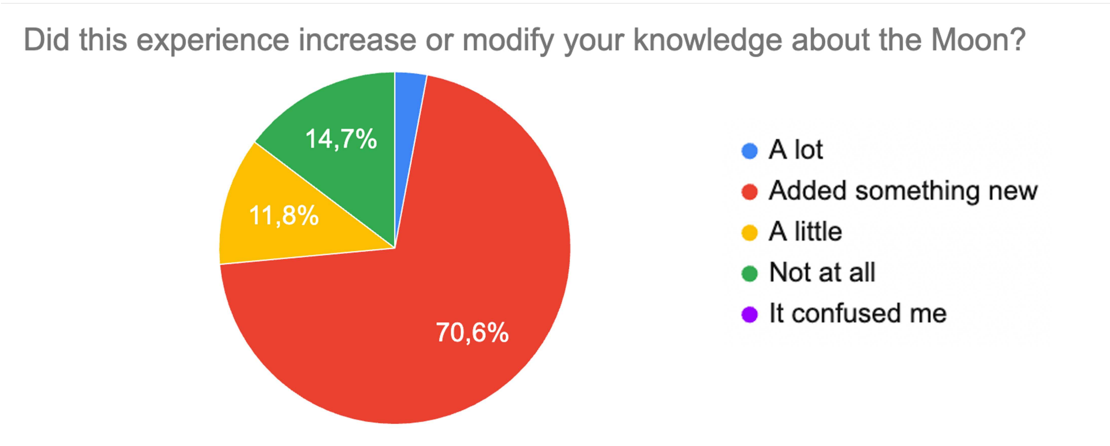


Figure 6.4: **Public** - Pie chart for the question regarding the increase of knowledge.

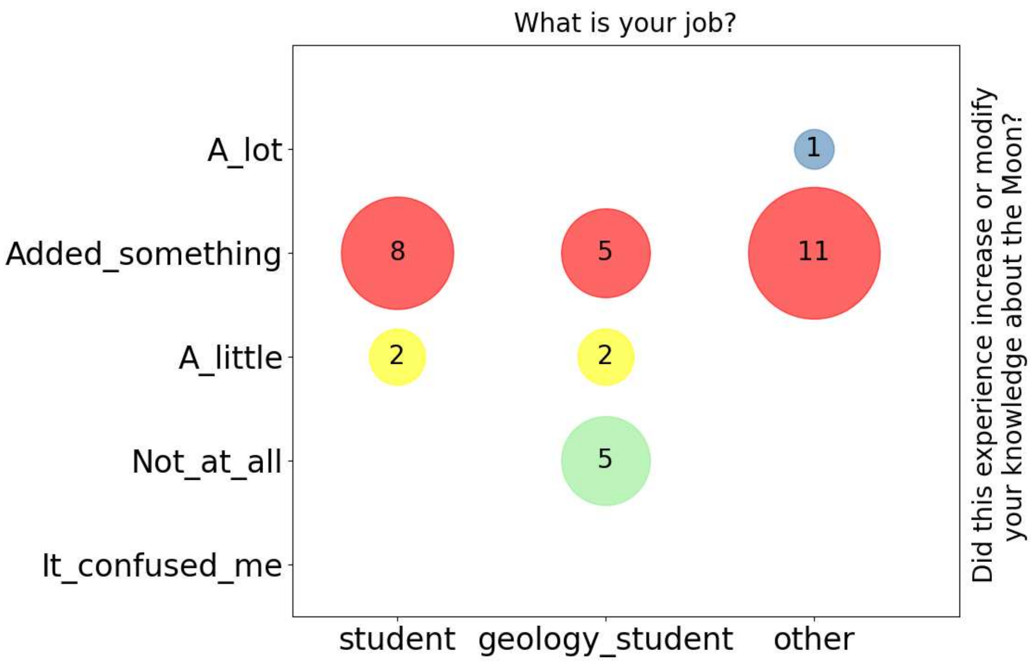


Figure 6.5: **Public** - Scatter plot: increase of knowledge vs job. The dimensions of the spots represent the frequency of the related couple of answers, reported also by the number inside the spot.

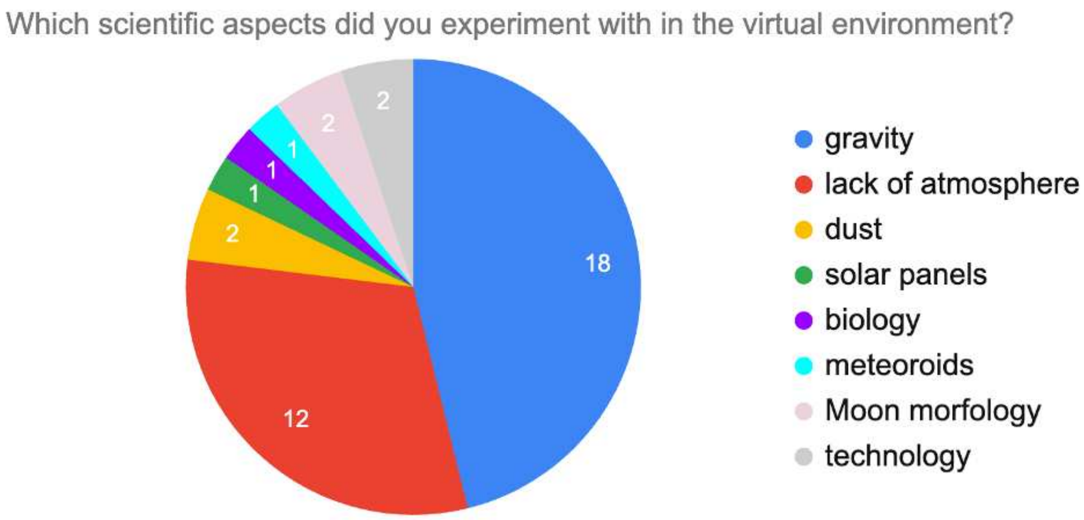


Figure 6.6: **Public** - Pie chart collecting answers to the open question regarding scientific contents. Note that people were allowed to report multiple aspects.

tasks result less impressive and memorable for the audience. The main reason might be identified in the level of focus that is put on the concepts during the task phase with respect to the first part of the experience, where the user is slowly leaded through the experimentation of the scientific concepts while. It must be noted that these result might be affected by a selection bias due to the Game Over chance: we do not know how many users actually completed their task, and for some of them, it is possible that the experience ended before the concepts connected to the tasks were proposed.

Nonetheless, even those concepts that reached a smaller number of users provide us with significant insights. The themes of lunar morphology and technology are mentioned even though they are never actively addressed during the experience. This indicates that the experience ensures a level of immersion that allows the majority of the users to infer content directly from the environment around them.

6.1.2 Scientists feedback

The feedback requested from members of the scientific community differs somewhat from that requested from the general public. On the one hand, we were interested in understanding whether the virtual reconstruction of the lunar environment was realistic and scientifically accurate; on the other hand, it was important to gather scientists' opinions on the effectiveness of a product like MOON RESCUER in transferring scientific content. Finally, we requested a general opinion on the satisfaction levels provided by the experience. The questionnaire is presented in Table 6.3. As in the previous case, in addition to the questions concerning the three aspects just mentioned, there were some questions useful for profiling the users. For the scientists, mostly closed-ended questions were used, but they were also given the opportunity to provide suggestions for future improvements to the experience.

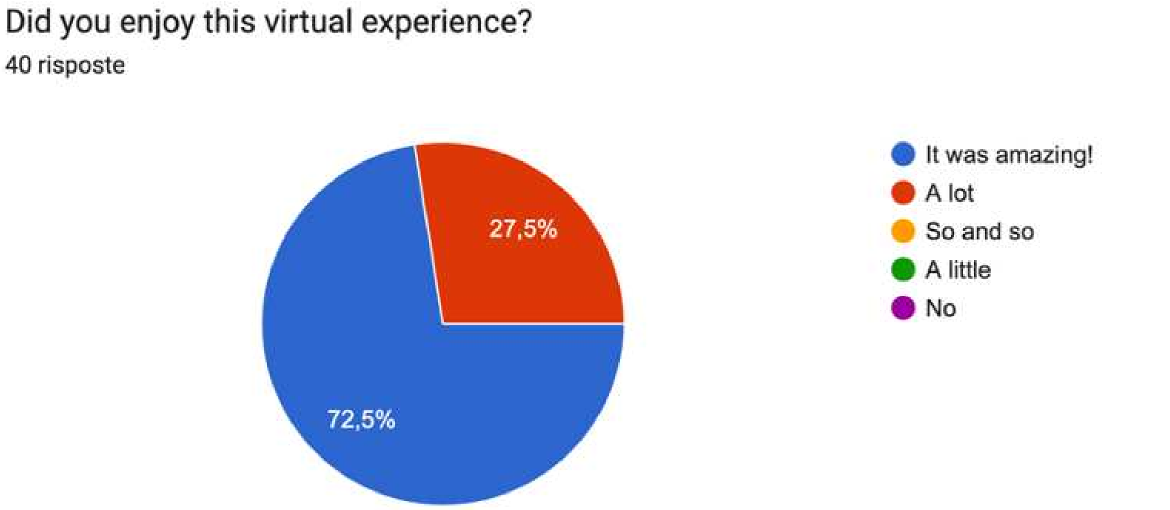
Table 6.3: Questionnaire for scientists

Aspect	**Question**	**Kind of answer**
General opinion	Did you enjoy the VR experience?	Multiple choice
Profiling	Did you ever test a virtual reality experience before?	Multiple choice
Realism	How did you feel movements and interactions within the virtual environment (comfort and realism)?	Multiple choice
Realism	How is the lunar environment represented?	Multiple choice
Effectiveness	How much is this experience effective in disseminating concepts about the lunar environment?	Multiple choice
Profiling	What is your role in research (Student, PhD, Post-Doc, Researcher)?	Open

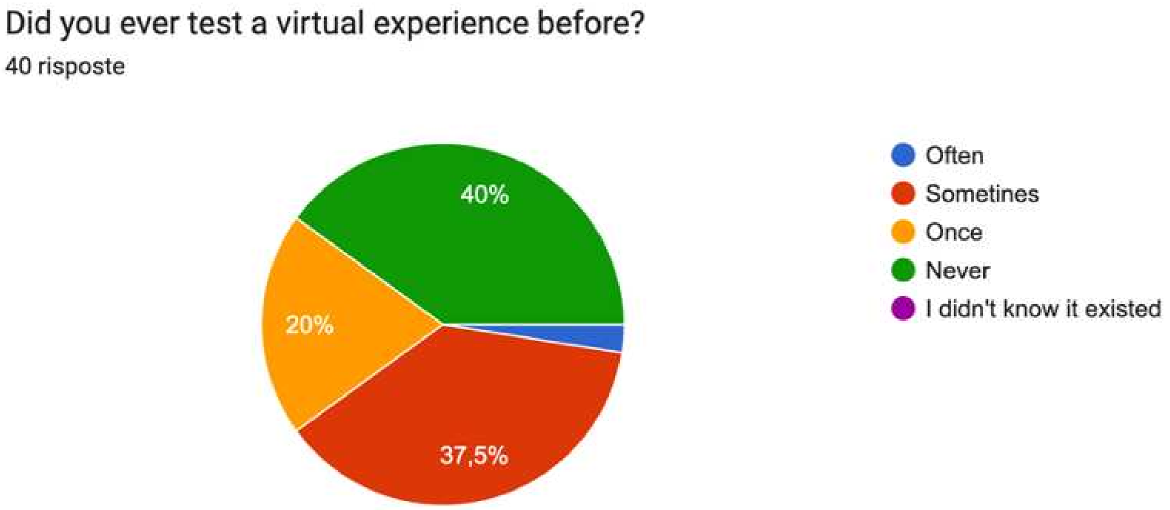
MOON RESCUER was presented to scientists at various career stages in astronomy and planetary sciences during conferences and meetings across Europe. Up to 40 feedback responses were collected. Typically, the tests took place in relatively small and not always isolated spaces, so the role of the facilitator - who, in these cases, was always the developer - was crucial.

The results of the questionnaires show that the general opinion of scientists about the MOON RESCUER experience is decidedly positive. No tester expressed a low or moderate level of satisfaction, and even 72% of users gave the experience the highest possible rating (Figure 6.7a).

Clearly, this is a result that needs to be contextualized: 40% of the scientists had never tried a virtual experience before MOON RESCUER, while only 2.5% (a single person among all respondents) were familiar with this type of media (Figure 6.7b).



(a)



(b)

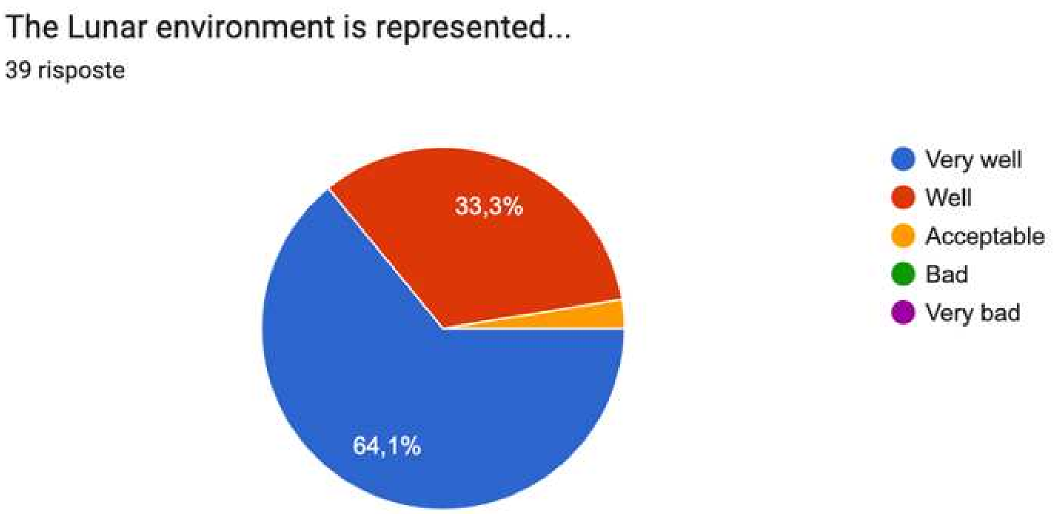
Figure 6.7: **Scientists** - Pie chart for the questions regarding a general opinion about MOON RESCUER (a) and previous experience with VR (b).

This means that a significant fraction of the interviewed users did not have many points of comparison to relate to the MOON RESCUER experience. However, the scatter plot in Figure 6.9 shows that the positive judgment towards the experience is quite independent of the users' familiarity with this type of technology.

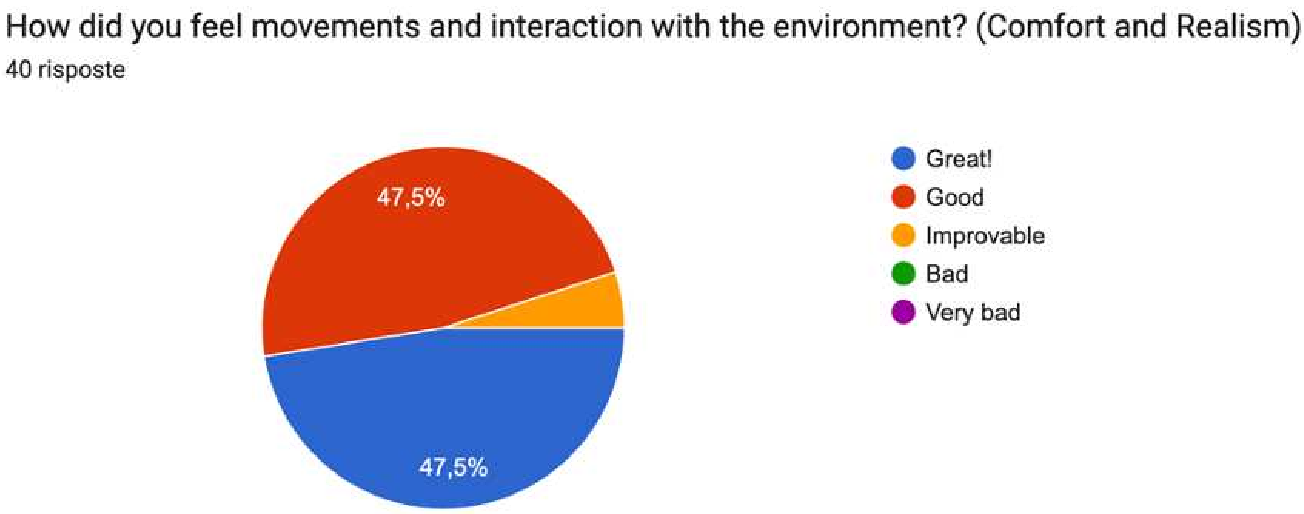
More than 97% of scientists express a positive opinion about the accuracy of the representation, and 64% give it the highest possible rating (Figure 6.8a). Similarly, the evaluations regarding the comfort and realism of the movements and interactions with the environment are also positive, with 95% of users expressing a favorable opinion (Figure 6.8b).

Finally, all the interviewed scientists agree on the effectiveness of MOON RESCUER in terms of communicating scientific concepts. 65% of the respondents rate the experience with the highest value on the proposed scale of effectiveness (Figure 6.10).

The scatter plot in Figure 6.11 shows the distribution of ratings on the communicative effectiveness of the experience in relation to the position of the respondents. Here, we also observe a fairly constant trend: however, it is notable that the majority of researchers tend to provide extremely positive feedback.



(a)



(b)

Figure 6.8: **Scientists** - Pie chart for the questions regarding the realism of the lunar environment reproduction (a) and the comfort and realism of movements and interaction (b).

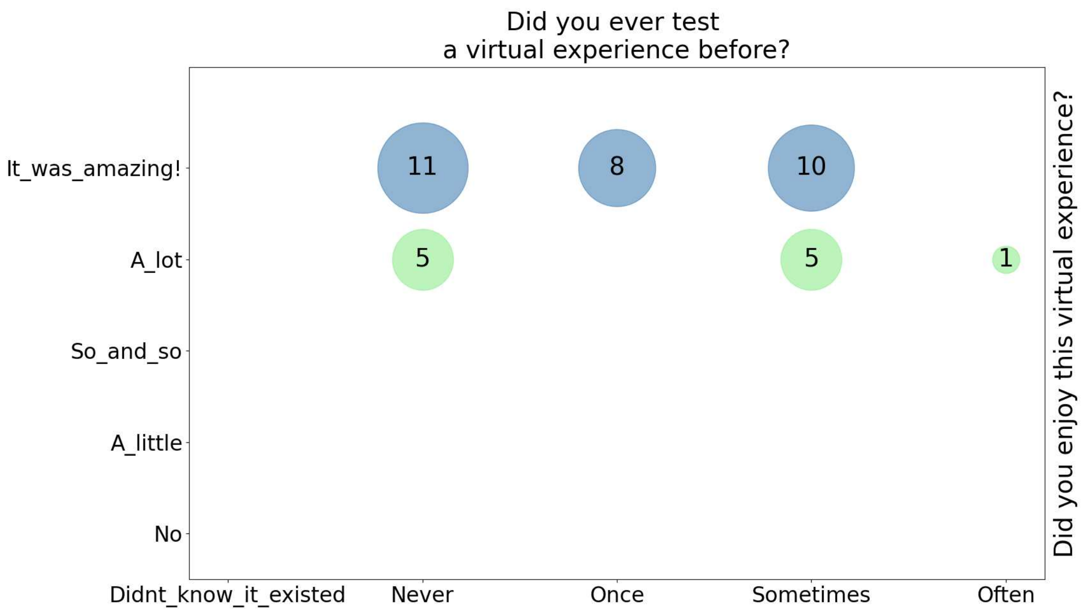


Figure 6.9: **Scientists** - Scatter plot for answers reported in Figure 6.7. The dimensions of the spots represent the frequency of the related couple of answers, reported also by the numbers inside the spots.

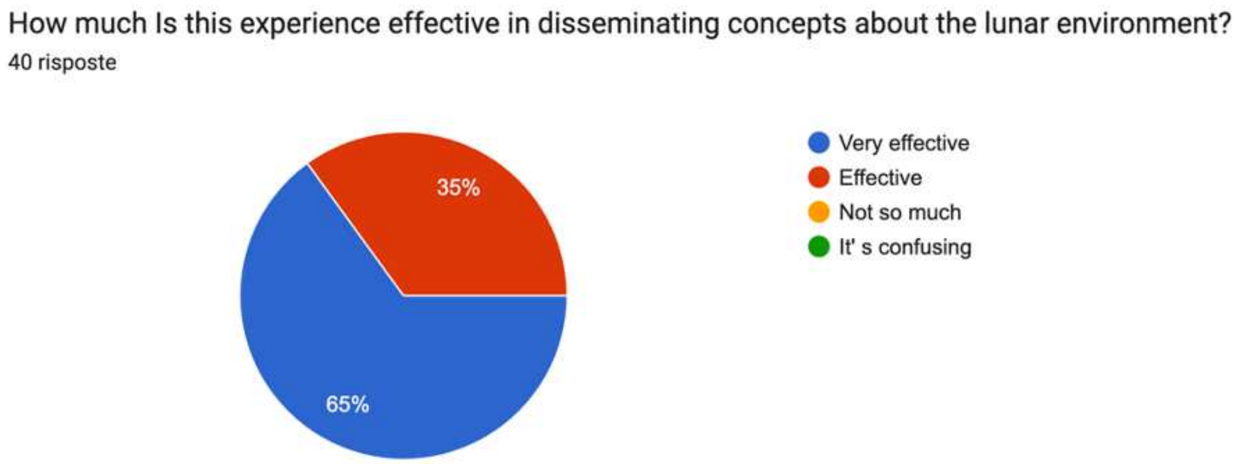


Figure 6.10: **Scientists** - Pie chart for the questions regarding the communicative effectiveness of the VR experience.

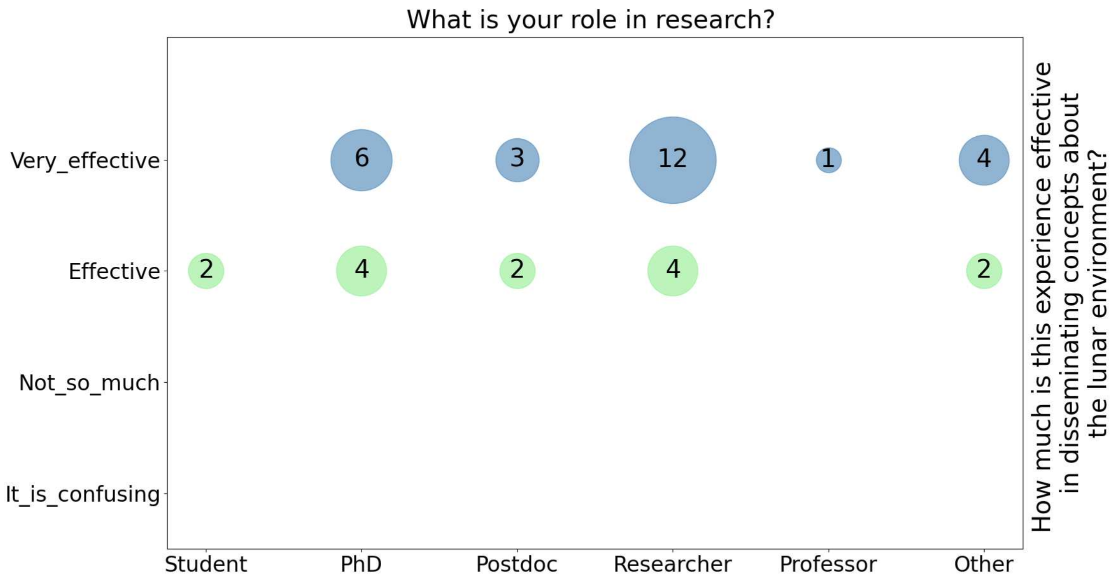


Figure 6.11: **Scientists** - Scatter plot: perceived communicative effectiveness vs role in research. The dimensions of the spots represent the frequency of the related couple of answers, reported also by the number inside the spot.

6.1.3 Facilitation

The role of the facilitator is often crucial when presenting a virtual reality experience to the public. Explaining how to wear the headset, how to move, and how to use the controls within the virtual world are necessary preliminary operations, especially when the user does not have much experience with this type of technology.

In all contexts where MOON RESCUER was presented, the role of the facilitator was primarily fulfilled by the person who developed the experience or alternatively by a properly trained individual who had previous experience with MOON RESCUER.

The first aspect that made the presence of the facilitator essential was related to the instructions to be provided to the user. Often, the noise in the environments where the tests were conducted made it difficult for users to hear the instructions delivered via audio (Figure 6.12). The only environment that proved free from this type of problem was SPARKme: the relatively isolated space dedicated to MOON RESCUER allowed users to hear the instructions without interference (Figure 6.13). This does not mean that the facilitator did not have to support the users, but at least it was never necessary to repeat the instructions verbally.

A fundamental element that emerged from the tests is the importance of mirroring. For the facilitator, having the ability to see what the user sees is crucial for providing the necessary support, guiding the user through the virtual world when they are disoriented, and helping them solve small problems that may arise during the experience. On some occasions, due to connectivity issues, mirroring was interrupted, and communication between the user and the facilitator became much more difficult. Often, in these cases, users took much longer to complete the experience, and sometimes the Game Over occurred before the task was completed.

According to the facilitator's impressions, the two elements that users appreciated the most were throwing balls and driving the vehicle. During these activities, users were very entertained, and their level of engagement was high. Immersion was total, to the point where interaction with the facilitator was often minimized.

Observing how different users interacted with the VR product, the facilitator consistently noted a trend in line with what is expected for this type of technology. Younger users tend to learn quickly how to interact with the virtual environment, while older individuals tend to show more difficulty and are more prone to disorientation. The categorization is not clear-cut, and there are exceptions on both sides. Some people, even young ones, struggled to use the controls, and in these cases, facilitator support was necessary.

Finally, an aspect that emerged rarely but deserves significant attention is the issue of accessibility. Users with motor disabilities or a strong propensity for motion sickness were unable to enjoy the experience. As discussed in Section 5.3.4, movement management is one of the most problematic aspects in the development of a VR product: on one hand, people with motor disabilities would benefit from the possibility of moving via controllers or teleportation; on the other hand, as we have seen, these movement mechanics tend to exacerbate the onset of motion sickness.

Figure 6.12: Testing the experience with scientists at *XIX Congresso Nazionale di Scienze Planetarie* (Bormio, Italy). The test was made during a poster session and the room was so noisy that the user was not able to listen to the instructions via audio. The facilitator needed to stand close to the user to repeat the instructions.

Figure 6.13: Testing the experience with public at *SPARKme* (Matera, Italy). The facilitator was able to support the user from outside the dome.

6.2 Impact analysis

Evaluating the impact of a product designed for public engagement can be quite complex. Feedback is the primary tool for this purpose, although many other factors should be considered depending on the type of activity proposed. Quantitative results, as the number of people joining the experience, are still considered as impact indicators but their importance is considerably reduced with respect to some decades ago. Qualitative indicators are assuming a growing relevance as nowadays it is preferable to achieve a strong impact on few people respect to a week impact on large audiences.

In the case of MOON RESCUER, the numbers are low: aside from those collected from the scientific community, only 34 feedback responses were gathered. The reasons for this are partly due to the characteristics of the media used and partly due to the context in which it was proposed. MOON RESCUER is a single-player experience lasting about 6-7 minutes, requiring a specific device and a floor area of at least 9 m^2 to function as the virtual room. Given the technical constraints, with only one headset, it is possible to offer the experience to no more than 7 people per hour. To achieve a higher rate, it is necessary to have a larger number of devices and sufficient space to accommodate corresponding virtual rooms. These are not trivial resources even for cutting-edge visitor centers, planetariums, and scientific festivals. For instance, tests at SPARKme were conducted with only one device. Moreover, the venue hosting a VR experience like MOON RESCUER often offers many other types of activities, and only a fraction of visitors actually use the experience. The number of feedback collected is also impacted by the fact that less than 50% of users actually complete the questionnaire. However, this limitation is not insurmountable: the general positive reception among the public convinced SPARKme to acquire a Meta Quest 2 device and keep MOON RESCUER within its visitor pathway. Other visitor centers are also interested in the product, and a broader distribution could, over time, allow for a significant number of users to be reached.

Despite the quantitative results, feedback shows that MOON RESCUER has proven to be highly effective qualitatively in terms of engagement. The target audience, the general public, and scientists all appreciated the virtual experience. Positive feedback from questionnaires is complemented by external impressions: when a user wore the headset, people nearby, even if not actively participating in the experience, displayed curiosity and enjoyment. The involvement of third parties was even stronger when mirroring allowed them to see what the headset user was seeing. In any context where it was proposed, MOON RESCUER created a very positive atmosphere. With few isolated exceptions, the management of movements and interactions was appreciated by users, as it maintained a high level of immersion without causing discomfort or disorientation. User responses indicate that MOON RESCUER effectively leveraged VR immersion to engage users in its narrative, temporarily transporting them to an alien environment and generating a strong and positive emotional impact. Many users explicitly reported feeling "engaged" as if they were "part of the environment" they were immersed in. This engagement made them particularly proactive in exploring and discovering the new environment. This confirms that MOON RESCUER is a virtuous example of leveraging VR capabilities for engagement.

Judging by the interview results, the impact of MOON RESCUER in terms of communicating scientific concepts was of medium level. Excellent feedback was received for those concepts addressed in the first part of the experience: lunar gravity and lack of atmosphere. The content in the second part of the experience, focused on task completion, proved less impactful and failed to resonate across all users. These results lead us to reflect on the gamification dynamics: while gamification makes the experience challenging, it should be implemented without compromising the user's ability to internalize content. The presence of a timer in the second part of the experience directs the user's focus towards actions needed to complete the task rather than on the content. In contrast, in the first part, users are guided to perform actions calmly, and concepts are clearly and comprehensively conveyed through audio. Another interpretation is that content related to each task was grouped within the same storytelling: content about solar panels is accompanied by content about dust, just as content about food production is paired with content about micrometeoroids. These choices were made during development with the idea of including more content, but they likely compromised its effectiveness: user attention is limited, and dividing it among various contents complicates information retention. On the other hand, in the first part, the user focuses entirely on the proposed content, as they are guided step by step in the actions to be performed. An interactive experience that aims to actively engage the user in exploration and learning cannot be structured in a fully guided manner. The fact that users have the freedom to explore and focus on certain concepts rather than others is crucial in the scientific communication dynamic intended for this project: it is not the virtual world that informs the user (*informatiom push*) but rather the user who interrogates the virtual world (*information pull*) (Cybenko and Brewingtont, 2011). In this sense, the fact that all scientific content proposed within the experience reached at least one user is a positive feedback for this approach. The opinion of scientists, who positively assessed the experience for both the accuracy of representation and effectiveness in conveying scientific content, confirms the high level that MOON RESCUER achieves as a scientific communication product.

7 Conclusion

The final goal of this research project is the characterization of virtual reality in the field of public outreach. Such an analysis involves framing the results obtained throughout the project — from the initial choices to the analysis of final feedback, passing through the development process — from various perspectives. To conclude this dissertation, we present considerations on the different aspects where this project has contributed to broadening the understanding of use of VR for purposes related to scientific communication and the promotion of research.

The development process highlighted several critical points and brought forth some successful approaches to tackle the more complex aspects. A simple and comfortable user experience, supported by guidance provided through audio recordings, has the advantage of enhancing user immersion within the virtual environment while minimizing instances of disorientation. Movement based on tracking and the use of a vehicle for long-distance travel prove to be a good compromise for managing movement, as they allow broad accessibility to the virtual environment and ensure a stimulating exploration while preventing issues related to motion sickness. The narrative is engaging and helps, on one hand, to coherently connect different aspects of the experience – scientific content, aesthetic elements, mechanics – and on the other hand, to place the user at the center of the experience, giving it an attractive and engaging structure. Similarly, gamification dynamics and interactions with virtual objects prove effective both for user engagement and for conveying content. The results obtained from the design and development process carried out in this work provide an important foundation for the future development of virtual reality products aimed at public engagement. The use of the MDA model proved effective for experience design, while development based on the refining cycle *test-feedback-problem solving* led to the resolution of various issues through original and diversified approaches. In addition to providing a starting point for further VR products, the development of MOON RESCUER has allowed the acquisition of a series of skills and perspectives applicable to the broader field of activity design for public engagement.

This research project has contributed to structuring a multilateral framework for the development of a VR public outreach product, serving as a potential reference for future productions. The direction identified through the development process of MOON RESCUER, enriched by collaborations among various contributors, outlines a path that could be followed in the future with fruitful results. Combining the expertise of individuals with diverse backgrounds, professional skills, and perspectives enables the development of more complex and effective activities in various aspects. We have seen how the design of a VR experience must simultaneously consider the quality of sensory stimuli—ensuring the accuracy of the reconstructed world, the communicative effectiveness of the content, and accessibility in terms of user experience. In an ideal collaborative context, scientists would be responsible for the accurate design of the virtual world and its elements, based on scientific data or, where necessary, plausible models. Communicators and educators, on the other hand, should focus on identifying effective strategies for delivering content—such as storytelling, game-based learning, tinkering, etc.—through the virtual medium, always considering the context of use and the target audience. Finally, developers would be tasked with the actual creation of the virtual world and the experience itself. This research highlights how, during the development process, problems and solutions related to different aspects of the product often intersect, demonstrating that the most suitable context for developing an effective VR experience is one that prioritizes interconnection over compartmentalization. The various facets of the project must work in synergy, embracing compromises and seeking to turn limitations into opportunities.

Beyond technical development, the public engagement dimension related to the relationship between internal and external actors of the scientific community has been fruitful. Interaction with members of the scientific community made it possible to create a product with good realism in terms of visual representation and accuracy of the themes. On the other hand, interaction with professionals in extended reality and communication was crucial to creating a product that was both effective and appealing to the public. Once development was completed, the testing phase allowed for collaboration with the SPARKme visitor center, which hosted part of the tests. This strengthened the collaboration between INAF, the promoter of this research project, and the visitor center, forming a bridge between academia and the third sector, one of the fundamental layers on which communication in the public engagement model is based. The presentation of MOON RESCUER at national and international conferences has attracted the attention of additional visitor centers, and new collaborations in this regard will be possible in the coming years. Finally, the project reports excellent results regarding the feedback MOON RESCUER received from both the public and scientists. Feedback from the public indicates that the virtual experience achieved a high level of user engagement. We conclude that the immersion and interactivity of this medium were excellently exploited, ensuring active, enjoyable, and emotionally satisfying participation. The experience shows good results in terms of effectiveness in conveying scientific content: confirmation of this comes from both public and scientific feedback.

Operational tests opened interesting reflections on what might be the most suitable context for activities like MOON RESCUER. Tests at SPARKme were conducted in a dedicated space in the visitor path of the center. This facilitated user independence compared to other contexts, where active and continuous support from a facilitator was required. Activities like MOON RESCUER are much more effective in a dedicated context, although this inevitably limits public participation in terms of numbers. The fact that the experience is single-player is an intrinsic limitation, but this can be overcome by using multiple devices and offering the experience to multiple users simultaneously, each in a dedicated space. However, even under optimal conditions, a single facilitator cannot support more than 2-3 users at a time, so increasing the number of users requires increasing the number of facilitators as well as expanding the necessary spaces. This combination of factors can make using an experience like MOON RESCUER in a school context complex, mainly due to logistical challenges related to space and timing. The most suitable context remains that of science festivals and visitor centers, where space, time, and support staff can be dedicated to the virtual experience.

Future developments of this research could move towards overcoming the identified limitations. The introduction of new features within the MOON RESCUER application could expand participation on a larger scale. Implementing a multiplayer mode could allow multiple users to enjoy the experience in a shared local space, or users in different locations to access the same virtual environment via connection to specific online servers. Beyond some changes to the narrative, interaction dynamics, tasks, and especially user experience support, such an expansion of the experience presupposes public accessibility to the MOON RESCUER application. Currently, the MOON RESCUER APK file can be installed on any Meta Quest 2 but only as a third-party application, requiring a specific sharing link and particular installation methods. Work is already underway to make the application available for free on the Meta online store, so it can be accessible to anyone who owns a Meta Quest 2 headset. Another way to expand the functionality and audience of the experience could be to explore mixed reality. This technology could allow for the participation of a larger number of users, some operating in the real space and others in the virtual space at the same time. The experience design would need to be reshaped, and new studies would need to be conducted on how to set up the real space in a way that maintains visual and narrative consistency with the virtual environment. These design aspects would be more complex than the technical aspects: in fact, the Meta Quest 3, a relatively affordable device that supports mixed reality, is now available on the market. Since it is the successor to the Meta Quest 2, the framework of the virtual experience – environment, 3D objects, interactions – could be reused, and it would only be necessary to design and implement new features and use the new drivers. Beyond multiplayer, store publication, and MR experimentation, minor additions are planned for the MOON RESCUER application: new tasks connected to other aspects of future exploration and the possibility of taking a tour of the lunar environment independently of the narrative are already in the planning phase. The issue of accessibility is more complex: movement based on tracking is problematic for people with limited mobility, and likewise, receiving information via audio poses an insurmountable barrier for those with hearing impairments. Much deeper studies on user experience are needed in this regard, but the iterative process of designing, testing, and problem-solving carried out during the development of MOON RESCUER seems capable of addressing even such complex challenges. In this sense, this research has provided important insights and allowed the development of skills that will prove very useful for future developments in the public engagement sector.

Looking to the future and beyond MOON RESCUER, this research positions itself within a field that has only been partially explored. The characterization of VR achieved in this project is certainly not exhaustive. There remains ample room for further studies that could investigate aspects that, due to the way this work was structured, were either overlooked or only briefly explored. As mentioned earlier, the multiplayer experience is an area of investigation that could unveil entirely new potentials and overcome some of the limitations observed in experiences like MOON RESCUER. Further studies in this regard should aim to determine whether a local multiplayer setup—with multiple users operating in the same physical space or context—or an entirely online multiplayer configuration would be more effective. In the former case, space constraints remain a key limitation, though the physical presence of a facilitator could provide support and maintain order. In the latter case, the software would need to be optimized to address user de-synchronization issues, either autonomously or through an online facilitator. On the other hand, the possibility of having multiple users simultaneously could make interactions with the virtual world and between users particularly rich, opening up a wide range of design possibilities for user experience, storytelling, and gameplay dynamics. Another intriguing area for investigation is the use of auditory stimuli. Today, most virtual experiences are primarily based on visual stimuli. However, in the fields of data visualization and public outreach, the technique of sonification is gaining traction. Combining these two technologies could lead to the design of innovative experiences with different communicative approaches. Clearly, careful attention would need to be given to the issue of disorientation, which often characterizes VR experiences. Further studies could also focus on the impact of VR experiences in public outreach. While this research has highlighted the significant engagement potential of this medium, we lack statistically significant results regarding the transfer of scientific concepts. Future studies will be necessary to determine whether certain concepts are more effectively conveyed through this medium or whether specific communication strategies are more suitable for particular types of content.

Although VR technology is now mature enough to enable the creation of products like MOON RESCUER, which are already effective in science communication and research promotion, new studies are needed to understand how to expand the medium's utility and effectiveness. This research project, which involved the design, development, and testing of MOON RESCUER, aims to provide a valid operational framework and serve as an effective case study for all future research and developments in this field.

A

Appendix

This appendix is dedicated to the description of the main elements that make up the scenes in Unity. The description is not exhaustive, as Unity offers a much broader range of possibilities than those explored during this research project. Nonetheless, in this appendix, the reader can find a description of the properties and components of all the elements that compose the scenes in MOON RESCUER. The descriptions provide the necessary level of detail for the reader to understand how the elements and their components were utilized during the development phase. For more detailed information, please refer to *Unity User Manual 2022.3 (LTS)* (n.d.), from which the information provided here has been extracted. To avoid overloading the reading, we group the elements into sections. In each section, different subsections are dedicated to subcategories of elements or to specific properties of the same. The structure, therefore, varies slightly depending on the elements described, but the schematic approach that characterizes it has been designed to allow the reader to easily navigate through the properties of the various elements.

A.1 3D Objects

In this section, we will discuss *3D Objects*, which are the elements that the application user will see during the experience. Very common components for most of these objects include *Transform*, *Mesh Renderer*, *Colliders*, *Materials*, *Rigid Body*, and *Scripts*: a specific subsection will be dedicated to each of them. There are other types of objects with different components, which will be discussed in separate sections later on. In this section, when we use the term *objects*, we are always referring to *3D objects*.

A.1.1 Transform

The *Transform* component identifies the dimensions, position, and orientation of the object (through the *Scale* and *Position* vectors and the *Rotation* quaternions, respectively) within the virtual space. This component is linked to the concept of object hierarchy: Unity allows for the parenting of two or more objects. When two objects are parented, one object assumes the role of *parent* and the other of *child*. The parent object becomes the origin of a new reference system, and the Transform component of the child object refers to this new reference system. The child object thus has two reference systems: the global reference system of the entire virtual space, known as *World*, and the parent object's reference system. If the Transform of the parent object is modified, the child object will undergo the same changes relative to the World, but the values of its Transform component will remain unchanged, as they are referenced to the parent object. Multiple child objects can share the same parent, and each child object can, in turn, act as a parent for other child objects. This hierarchical division of objects is very useful as it allows for the management of systems composed of a large number of objects, in addition to providing a clear and organized framework during development.

A.1.2 Mesh Renderer

The term *Mesh* in computer graphics and 3D modeling refers to a network of vertices, edges, and faces that defines the shape of a virtual object. Unity allows for the creation of objects with simple types of Meshes: cubes, spheres, planes, etc., or the importation of objects created using other modeling software, with arbitrarily complex Meshes. Various formats of 3D objects are supported, but in this project, only obj and fbx files were imported, previously created or edited using Blender software. The 3D models must be imported as assets and then added to the scene as objects. All objects rendered in a scene are equipped with a *Mesh Renderer* component, which also allows for setting the interaction of the object with ambient lighting: determining whether the Mesh casts shadows, receives shadows from other Meshes, or contributes to the lighting in some way.

If the Mesh is composed of several *elements*, the Mesh Renderer will also list all the elements that make up the Mesh and the Materials associated with them.

A.1.3 Materials

Materials are components that manage the visual characteristics of the object and how it reacts to ambient lighting. It is possible to make an object opaque, transparent, reflective, metallic, or even capable of emitting its own light by setting the characteristics of its Material component. A material is effectively an asset that can be created within the Unity environment or imported externally. Once created, the Material can be associated with one or more objects as a component, but all edits made to the Material are done directly on the asset, not on the material of the individual object. This means that if several objects share the same material, modifying that material in one object will affect the others as well.

As mentioned in the previous subsection, an object can have several Material components associated with the different elements that make up its Mesh. The information that links elements and Materials is encoded within the object's asset: when the asset is loaded into the scene, this information is explicitly listed in the Mesh Renderer. Sometimes, Unity does not recognize the materials encoded within assets imported from external sources. This is because those materials were created using specific tools from other modeling software. There are processes to make external materials compatible with Unity but often it is possible to resolve the issue by extracting the materials from the imported asset and modifying them, or by replacing them with materials created anew directly within Unity. Whether extracted from objects or created from scratch, Materials are effectively assets of the project.

In terms of diffusion, the Material component allows the developer to set a specific color for the object or import a two-dimensional image, known as a *texture*, which is then reproduced on the object's three-dimensional surface. Just like materials, textures can be imported into the project as assets and later associated with different materials. The information that describes how the texture image is mapped onto the object's surface is called *UV Mapping* of the texture. If an asset has a texture, often the mapping is encoded within the asset file, but it is also possible to extract this information from the file and associate it with the material. In this project, most objects have material components with textures, in some cases very complex ones.

A.1.4 Collider and RigidBody

Colliders and Rigid Bodies are the components responsible for managing the physics of the object. Specifically, colliders constitute a geometric structure that describes the physical surface of the object. Colliders are used by Unity's engine to calculate the results of collisions between different objects. It is crucial to note that this structure often does not coincide with the rendered Mesh of the object but approximates its characteristics. In this project, colliders of four shapes were used: Box, Sphere, Capsule, Wheel. Objects with complex Meshes were equipped with multiple colliders to better approximate their shape. Reducing rendered objects to simpler geometries is much less computationally expensive for the engine.

The RigidBody component, on the other hand, manages how the object reacts to different forces in the virtual space: it is possible to set the mass of the object, its friction coefficient, and any constraints on its kinematics. One specific option in this component is *Use Gravity*: Unity has a pre-set tool that generates a constant gravitational field in the virtual space with arbitrary intensity, but only objects with a RigidBody component where *Use Gravity* is selected are actually affected by the field.

A.1.5 Script

Multiple *Scripts* in C# can be associated with each object. The scripts used in this project belong to a specific class type in Unity called *MonoBehaviour*. This class type is structured with life cycle functions that simplify the development and management of the instructions coded in the project: *Start()* and *Update()*. The Start() function is called once as soon as the script is activated. If the script is always active, this function will be called at the application's launch. When Start() is called, all the instructions within it are executed in the order they appear. The Update() function is called once per frame for as long as the script remains active. Every time it is called, all instructions within it are executed. The presence of this function facilitates the development of instructions that need to be repeated over time and the implementation of the checking-interaction-updating chain that characterizes interactive experiences.

We will not delve into the technical details of programming in C#, but it is worth mentioning a few relevant aspects.

All elements of a script (classes, methods, variables) can be *public* or *private*. A private element is accessible only within its scope in the script. A public element, however, is visible and accessible even outside its scope.

It is possible to create new distinct functions with public or private parameters within a MonoBehaviour class and then call them in the code, either in Start() or Update(). This offers the possibility of giving the scripts an organized architecture that facilitates both development and debugging.

Through scripts, it is possible to access the components of various objects in the scene, as long as they are public. This means that through scripts, one can also activate, deactivate, or modify the components of various objects, including other scripts. On the one hand, this greatly facilitates development: specific interactions between objects can be programmed through scripts that call other scripts under certain conditions, distributing the complexity of the interactions across various steps rather than managing it with a single code. On the other hand, debugging can be lengthy and difficult when many components of different objects are involved.

It is important to note that among the various assets within a project, scripts represent the most numerous type. The pre-loaded tools that Unity's engine uses to manage various aspects of the application are made up of scripts and groups of scripts associated with specific objects.

A.2 Camera

The *Camera* is a fundamental object for any project. It effectively represents the user's point of view of the scene: the rendering of the scene is done based on the Camera. At least, this is the role of the *Main Camera*, an object that must necessarily be present within any scene. Other Cameras can be added to the scene, allowing the application to display the scene from different perspectives. If only one Camera is present in a scene, it will default to the role of the Main Camera. Camera objects naturally have a Transform component and can have script components attached. However, the component that primarily characterizes them is the eponymous *Camera* component. Within this component, it is possible to set a series of parameters that control how the Camera renders the scene. We will describe some of these parameters, focusing only on those that played an important role in the project.

A.2.1 Field of View

The *Field of View* (FOV) has two dedicated parameters: the first, *FOV Axis*, determines the Camera's orientation (*Vertical* or *Horizontal*), while the second expresses the Camera's viewing angle, measured in degrees along the selected axis. In all the scenes of this project, a Vertical FOV with an angle of 60° was used.

A.2.2 Projection

This parameter defines how the Camera reproduces the perspective of the scene it is rendering. If set to *Perspective*, the objects in the scene are rendered with the perspective perceived by the Camera with its FOV, whereas the *Orthographic* value produces a uniform rendering that does not take perspective into account. When selecting an Orthographic Projection, the parameters related to the FOV are disabled, and a *Size* parameter is introduced, expressing the Camera's two-dimensional extent. The Orthographic Projection is widely used in applications composed of 2D scenes or scenes aiming for a 2D graphical rendering. For the Main Camera of this project, a Perspective Projection was always used, but we will see that Orthographic also found application during development.

A.2.3 Culling Mask and Layers

The *Culling Mask* allows one to choose which objects in the scene are actually rendered by the Camera. This process presupposes that each object in the scene is assigned to a *Layer*. All objects have this parameter, which allows them to be categorized into different groups. There are types of objects that already have a reference Layer, such as UI elements, but it is possible to create new Layers and assign each object to one of the available Layers. There is a *Default* Layer to which all objects are assigned if no specific Layer is designated. The Culling Mask parameter allows one to select which Layers will be rendered by the Camera: its list structure enables the inclusion and exclusion of various Layer entries at will, and only objects belonging to the included Layers will be rendered. The Culling Mask is very useful when multiple cameras are present in a scene, and one desires to assign secondary functions to a Camera: the scene can remain unchanged, but the secondary Camera can be assigned the rendering of only a limited number of objects.

A.2.4 Clipping Planes

This parameter also serves to determine which objects are actually rendered in the scene, but the selection is based on the distance from the Camera. It is possible to set two distance values (*Near* and *Far*) such that any object whose distance from the Camera is less than Near or greater than Far is not rendered. This parameter is useful when the virtual space in the scene is very large and full of objects: there is no point in burdening the application with the rendering of very distant objects. In this project, the default values of 0.01 m for Near and 1000 m for Far were chosen.

A.2.5 Target Texture

This option allows the Camera output, i.e., its rendering, to be sent to a *Render Texture*. A Render Texture is a specific type of texture that Unity constantly updates at runtime. The Render Texture is created as an asset and then imported into the Material of the object to which it is to be applied, just like any other texture. Therefore, to apply the rendering of a Camera to an object, one simply creates a Render Texture, sets it as the Camera Target Texture, and then imports this texture into the Material of the object. This allows for small additional screens in the scene that show the view of the scene, or part of it, from a specific point of view.

A.3 UI

User Interfaces (UI) are types of objects intended for managing interactions between the user and the application. *Buttons* are the perfect example of UI objects. A button is not a physical object, but it still has its geometry and visibility within the virtual space; it can be pressed, pointed at, or selected, depending on the input system implemented in the project, and it can have various purposes within the context of the application. Buttons are two-dimensional objects that require the presence of a reference plane, called a *Canvas*. During development, when a button is created, it appears in the Scene and the Hierarchy along with its Canvas, to which it is associated as a child object.

A.3.1 Canvas and Buttons

Canvas and buttons have a specific type of Transform component called *Rect Transform*: this is equipped with parameters that help the developer easily manage the dimensions and relative positions of these objects. Among the Canvas components, the eponymous *Canvas* component is important, particularly the *Render Mode* parameter, which expresses which of the three rendering modes of the Canvas is used:

- Screen Space - Overlay: the Canvas is fixed at the top center of the screen displayed to the user;
- Screen Space - Camera: the Canvas is fixed relatively to a specific Camera;
- World Space: the Canvas is fixed relatively to the World, meaning it behaves like any other object in the virtual space; the user can move around it or change the perspective from which they view it.

Among the Button components, the eponymous *Button* component is important, featuring a simple tool (*On Click*) to manage what happens in the application when the button is pressed. This tool is useful because it allows one to bypass the step of boolean logic in scripts and manage simple single instructions directly. We will see that similar tools are also present in the XR Interactable components in section A.4.

To code more complex instructions, it is possible to add script components to buttons. In this case, the (*On Click*) tool is very useful because the script components of the button can be initially kept inactive, setting their activation through (*On Click*).

A.3.2 TextMesh

Buttons have a very simple aesthetic, although it is possible to add specific components to manage and enhance their graphical appearance. An alternative is provided by Text-Mesh objects. These are also two-dimensional interactive objects associated with Canvases, but unlike buttons, they have a specific component (*Text*) dedicated to writing and rendering text. Text-Mesh objects are simple yet refined and explanatory UI objects; it is also possible to add button and script components to these objects to manage interactions.

Considering all these features, as well as the role that UIs play in the virtual reality experience, it was decided to use only TextMesh UI objects for the final version of the project.

A.4 XR

eXtendend Reality (XR) objects are specifically designed for the development of virtual reality, augmented reality, or mixed reality projects. To manage interactions between the user and these objects, a specific object called *XR Interaction Manager* must be included in the Scene. This object is not rendered in the scene as it only has a script component of the same name, which contains the instructions that allow it to manage XR. Some specific packages must be included among the project assets for the XR Interaction Manager to function properly. These packages must include specific drivers for the device the experience is intended for, and consequently, specific input settings must also be configured. In particular, the *XR Interaction Toolkit* package provides a series of pre-developed scripts and tools for managing input (*Input Action Manager*), interactions, user tracking systems with their device (*Tracked Device*), and runtime object movement (*Locomotion System*). We will not delve into the description of all the elements of this vast toolkit, but will instead focus on the different types of XR objects used in the project and their main characteristics. The potential offered by the XR Interaction Toolkit is particularly extensive, but for understanding the development process and the operation of XR objects in the scene, the following description is more than sufficient.

A.4.1 XR Origin

An *XR Origin* object is designed to represent the virtual projection of the user within the scene (*Player*). It is possible, though not always necessary, to provide physical parameters to the Player: this is the purpose of the *Character Controller* component, which in this case replaces the Colliders. The object also has a script component that manages its relationship with the Camera to which it is associated. In fact, as soon as an XR Origin object is created, it automatically acquires a child object called *Camera Offset*, which in turn has three child objects representing the elements of the device:

- *Main Camera*: in addition to the Camera component, this object also has an *Audio Listener* component, which allows sound playback, and a component called *CameraTrackedPoseDriver*, which manages tracking. In a VR project, the Main Camera represents the virtual equivalent of the headset. It is important to note that the *CameraTrackedPoseDriver* allows rotation and position tracking to be enabled or disabled independently.

- *RightHand/LeftHand Controller*: each of these represents the virtual equivalent of the respective controller. The pointing of the controller is rendered on screen through a 3D line using the *Line Renderer* component; the *XR Interactor Visual* component allows editing the visual appearance of this rendering, while the *XR Ray Interactor* and *XR Controller* components respectively manage the interaction settings with objects (interaction distance range, object movement speed) and command settings (texts, movement tracking). Among the simplest commands coded in the XR controller are those for *Select* and *Activate* XR objects. Selection and activation are two different levels of interaction with an object: an object must first be selected and then it can be activated. In this project, it was sufficient to use only one level of interaction with the objects, so we always limited ourselves to programming only *Select* interactions.

Of course, the fact that these three objects are provided by default by Unity when the XR Origin is created is because the project includes the drivers and specific tools for the Meta Quest 2: these generate the objects with the necessary hierarchy and components, and also associate at the software level the Main Camera object and the Controller objects with the device systems.

A.4.2 XR Simple Interactable

In principle, any object can be an *XR Simple Interactable* because what characterizes these objects is the eponymous script component. Therefore, it is not a specific type of object, but a property, that of being interactable, which the object acquires with the XR Simple Interactable component. This provides a series of tools similar to the On Click we saw for the buttons in section A.3: the *Select Entered* tool, for example, is exactly equivalent to On Click for XR objects, as it allows one to manage what happens in the application when the object is selected by the user; similarly, the *Select Exited* tool manages what happens at the time of deselection. There are also the analogous *Activated* and *Deactivated* tools, which work the same way for the Activate command, and other specific tools that were not used in this project. Note that, for XR Simple Interactables to be selectable, they must have at least one Collider component, making them physically present in the scene.

A.4.3 XR Grab Interactable

Almost everything we have seen applies also to *Grab Interactables*. However, these objects are programmed to be "grabbed" and moved when selected. In the *Grab Interactable* component options, it is possible to specify the settings for how the object movement (still based on tracking) and other behaviors are linked to the controller movement and commands. This component also provides the same tools we described for Simple Interactables. Generally, Grab Interactables are objects that have a tangible role within the scene, so they usually have, in addition to Colliders, also Rigid Body and Mesh Renderer components: in this case as well, it is more of a property that any object can acquire thanks to the appropriate script component.

A.4.4 Locomotion System

Locomotion System objects can be associated as child objects to *XR Origin* objects. The role of these objects is to allow the XR Origins to move based on the commands provided by the user through the controllers. Locomotion Systems are equipped solely with script components that contain instructions for managing four types of movement. These preloaded scripts are named after the type of movement they produce:

- *Teleport provider*,
- *Snap Turn provider*,
- *Continuous Turn provider*,
- *Continuous Move provider*.

For each of these, it is possible to set the movement settings (speed, gravity interaction, etc.) and the commands to be provided through the controller to execute the movements (joystick or tracking).

A.5 Terrain

A *Terrain* is a particular type of object that acts as the ground in virtual space. It is a two-dimensional surface that can be modeled, textured, and embellished with details through specific tools. A Terrain has only two components: a *Terrain Collider*, which works exactly like colliders for 3D objects; and a *Terrain* component, which contains the editing tools of the object. We now present an overview of the main tools of this component.

A.5.1 Paint Terrain

This tool allows one to model the terrain once the asset has been included in the scene as an object: the tool provides a brush cursor that identifies the portion of terrain to be modeled and a series of characteristics that can be adjusted: height, depression, smoothness. This same tool also allows for adding various texture layers to the Terrain, thus managing its visual appearance.

A.5.2 Terrain Details

This tool, on the other hand, allows one to distribute specific details on the Terrain's surface, following different types of distributions and densities. A brush is also used to circumscribe the areas affected by the detail distribution. These details can consist of object-type assets, but it is important to note that the assets brought into the scene as Terrain Details are not objects: they do not enter the Hierarchy, and it is not possible to access their components. The details are reproduced in series and distributed on the Terrain as immutable copies of the original asset, presenting all and only its intrinsic characteristics.

A.5.3 Terrain Settings

This tool finally allows one to set the general settings of the Terrain, such as its Mesh resolution (i.e., its dimensions), its detail density, the way it reacts to light, etc. There are other tools that allow for adding further complexity and details to the Terrain, but since they were not used in the development of this project, we will not mention them.

A.6 Lights

Light objects are those that illuminate the scene. They possess Transform and Mesh Renderer components, so they have a geometry in space as objects. Other components can be added to the object to create specific visual effects. Here are two examples of visual effects, present in this project, that are created by adding specific components:

- *Lens Flare* is the effect that occurs in photographs or videos when the light source is within the Camera field of view and is due to the refraction of light within the optical elements of a camera;

- *Halo* is the effect by which luminous arcs form around the source and is mainly due to atmospheric refraction phenomena.

By modifying the parameters in their respective components, it is possible to set the size, brightness, and color of Lens Flares and Halos. In any case, these effects are just additional details, as the way Light objects actually project light into the scene is managed by the eponymous *Light* component: this offers different light types that can be emitted by the object, light settings, and color settings.

A.6.1 Type

This section determines the type of lighting the object will provide to the scene. There are mainly three types of lighting:

- a *Point Light* emits light isotropically from a single point of origin;

- a *Directional Light* emits light in the form of a plane oriented in a specific direction (defined by the Rotation within its Transform);

- a *Spot Light* emits light in the shape of a cone, with the *Range* and *Spot Angle* parameters defining the conical space effectively subject to illumination.

For all three types of lights, it is possible to set the *Color* and *Intensity* through the respective sections. As with Camera objects, Lights also have a Culling Mask section to select which categories of objects are actually affected by the light.

A.6.2 Shadows

The management of shadows is handled by specific options, independent of the type of Light. The *Shadow Type* option allows one to determine the contrast of shadows generated by objects interacting with the Light object. There are:

- *Hard Shadows*;
- *Soft Shadows*;
- the *No Shadow* case, where the Light does not generate any shadows.

For both Hard Shadows and Soft Shadows, it is possible to set the *Strength* and *Resolution*, which characterize their impact at the rendering level.

A.7 Other Elements

Before moving on to the next section, it is necessary to add some information about particular types of elements that do not fall under the categories listed so far but have played a role in the development of the application.

A.7.1 Light Settings

Beyond Light objects, scenes are characterized by ambient lighting, the characteristics of which can be set through specific tools. These are part of an asset called *Light Settings*: each project has a default Light Settings, but assets of this type can be created from scratch for each scene. Within the tools, it is possible to set the color, intensity, and diffusion of the light in the scene, as well as choose the background of the scene itself. The background can be created using specific materials called *Skyboxes*: these materials use a specific shader that allows their texture to be projected three-dimensionally onto the background.

A.7.2 Visual Effects

Beyond ambient lighting and Light objects, scenes can be enriched with details thanks to elements with a strong visual impact. These are not specific types of objects, but rather a series of components that, when used effectively, can greatly enhance the graphical rendering and animation of objects. *Particle Systems* are an excellent example of this type of component. The generation and movement of particles can significantly increase the computational load of the project, but such effects have great potential in terms of audience impact and make the scene much more lively and engaging. The tools within the Particle System component allow complete control over what happens to particles in the scene, both from a physical and rendering perspective.

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