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Corso di Laurea Magistrale in Ingegneria Informatica
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# An Educational Experience in Virtual and Augmented Reality to Raise Awareness about Space Debris

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*“Do fairies have tails? Do they even exist? Like them, this place is an eternal mystery... A never ending adventure!”*
Makarov Dreyar - Fairy Tail

# Summary

Space debris represent a threat to space missions, to operational satellites, and also to people and properties on the ground. When an uncontrolled object re-enters the atmosphere part of it is destroyed by the heat while between 10% and 40% of its original mass reaches the Earth's surface as fragments. These surviving fragments possess enough energy to severely damage what they hit and they also pollute the environment. In this thesis, we designed, developed, and validated an educational application in virtual and augmented reality to raise awareness about the space debris problem. Our application targets both people with some knowledge about space missions (such as aerospace engineering students) and people with other backgrounds. In particular, it aims at supporting the course of "Orbital Mechanics" at Dipartimento di Scienze e Tecnologie Aerospaziali (DAER) of Politecnico di Milano.

# Sommario

I detriti spaziali rappresentano una minaccia per le missioni spaziali, i satelliti operativi e anche per persone e proprietà sulla Terra. Quando un oggetto non controllato rientra nell'atmosfera, una parte di esso viene distrutta dal calore mentre una porzione compresa tra il 10% e il 40% della sua massa originale raggiunge la superficie terrestre in forma di frammenti. Questi frammenti superstiti possiedono sufficiente energia per danneggiare gravemente quello che colpiscono e, inoltre, inquinano l'ambiente. In questa tesi abbiamo progettato, sviluppato e valutato un'applicazione educativa in realtà virtuale e aumentata per la sensibilizzazione al problema dei detriti spaziali. La nostra applicazione si rivolge sia ad un pubblico esperto in fatto di missioni spaziali (ad esempio gli studenti di ingegneria aerospaziale) sia a persone con un altro tipo di formazione. In particolare essa mira a supportare il corso di "Meccanica Orbitale" tenuto al Dipartimento di Scienze e Tecnologie Aerospaziali (DAER) del Politecnico di Milano.

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# Chapter 1

# Introduction

Thousands of man-made objects orbit around the Earth at different altitudes. The European Space Agency (ESA) estimates that there are around 750000 objects larger than 1cm that are untraceable by current technology. However, only 6% of the known objects orbiting the Earth are active while the remaining 94% of them are inactive space debris.

Space debris represent a threat to space missions and operational satellites. Due to the high orbital speed, an impact with a fragment as small as 10cm or less can result in the partial or complete loss of a mission. When there is a risk of collision with space debris, operators must assess in a timely manner whether to perform a collision avoidance manoeuvre. Such maneuvers waste fuel that could otherwise be employed for main operations and often require a momentary suspension of the satellites' service, which can be infeasible because of the mission's constraints. Space debris also pose a threat to people and properties on the ground. When an uncontrolled object re-enters the atmosphere part of it is destroyed by the heat while between 10% and 40% of its original mass reaches the Earth's surface as fragments. These surviving fragments possess enough energy to severely damage what they hit and they also pollute the environment.

## 1.1 Our Objective

The objective of this thesis was the design, development, and validation of an educational application in Virtual and Augmented Reality to raise awareness about the space debris problem. Our application targets both people with some background knowledge about space missions (such as aerospace engineering students) and people with other backgrounds. In particular, it aims at supporting the course of "Orbital Mechanics" at Dipartimento di Scienze e Tecnologie Aerospaziali (DAER) of Politecnico di Milano. The target platforms are Hololens (Microsoft's Augmented Reality smartglasses), and ASUS Windows Mixed Reality Headset, a Virtual Reality head-mounted display. The application comprises a Story mode and an Exploration mode. The former is oriented towards the dissemination of information on the space debris problem to a general public. The latter targets a more experienced audience by allowing an educational stroll in near-Earth space.

## 1.2 Thesis Outline

The thesis is organized as follows:

- **Chapter 2 -** ***Space Debris*** describes the space debris problem. It explains how space objects are catalogued and why those that fall under the category of space debris pose a threat to current and future space missions. It recalls the history of space debris since the beginning of the space age and, finally, it gives an account of several mitigation measures for the problem.

- **Chapter 3 -** ***Virtual, Augmented, and Mixed Reality*** describes what are Virtual, Augmented, and Mixed Reality and presents their histories. It also provides an overview on the key technologies for Virtual and Augmented Reality.

- **Chapter 4 -** ***A Mixed Reality Experience for Space Debris*** explains the requirements and the objectives of the experience we developed. It describes how we designed the flow of the application and its architecture. Finally, it presents the technologies on which we based the development of the application and the main challenges encountered.

- **Chapter 5 -** ***The Space Debris Application*** illustrates, with the support of several screenshots, the various settings users find themselves in during the experience and the functionalities offered by the application.

- **Chapter 6 -** ***Experimental Results*** describes the responses of the public to the different prototypes of the application and its final evaluation with the students from the Video Game Design and Programming course of Politecnico di Milano.

- **Chapter 7 -** ***Conclusion*** draws some conclusions about our work and delineates future research directions.

# Chapter 2

# Space Debris

This chapter explains what is space debris and how it evolved during the years, why it poses a threat to current and future space missions, and, finally, some mitigation measures to counteract the problem.

## 2.1 What is Space Debris?

Every day thousands of man-made objects orbit around the Earth at different altitudes. They either occupy a Low Earth Orbit (LEO), ranging from 300 to 2000km of altitude, a Medium Earth Orbit (MEO), ranging from 2000km to 36000km, or a Geostationary Orbit (GEO), travelling at an altitude of about 36000km. The US Space Surveillance Network's data set[1] keeps track of more than 23000 of them, from 5-10cm of size in LEO and from 30cm-1m in GEO [15]. The European Space Agency (ESA) estimates that there are around 750000 objects larger than 1cm orbiting the Earth which are untraceable by current technology.[2] The number of tracked objects might increase by a factor of five as a new radar facility in the Pacific Ocean is to be turned on in 2019. Thanks to it, the US military will be able to locate fragments smaller than today's 10cm limit for LEO.

Only 6% of the known objects orbiting the Earth are active. They are called payloads (PL) and are currently carrying out the task for which they were designed. The remaining 94% of the tracked objects are inactive space debris and are divided in two classes: those that can be associated to a launch event and whose nature can be recognized, and those for which it can not be done. The latter ones are called *Unidentified (UI)*, while the former ones can be more specifically split based on their origin as [38]:

- **Payload mission related objects (PM):** space objects released as space debris which served a purpose for the functioning of a payload. Common

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[1] USSTRATCOM Two-Line Elements data set: `https://www.celestrak.com/NORAD/elements/`

[2] European Space Agency (ESA) website: `http://www.esa.int/Our_Activities/Operations/Space_Debris/About_space_debris`

examples include covers for optical instruments or astronaut tools.

- **Payload fragmentation debris (PF):** space objects fragmented or unintentionally released from a payload as space debris for which their genesis can be traced back to a unique event. This class includes objects created when a payload explodes (e.g. because of remaining fuel or failed batteries) or when it collides with another object.
- **Payload debris (PD):** space objects fragmented or unintentionally released from a payload as space debris for which the genesis is unclear but orbital or physical properties enable a correlation with a source.
- **Rocket body (RB):** space object designed to perform launch related functionality. This includes the various orbital stages of launch vehicles, but not payloads which release smaller payloads themselves.
- **Rocket mission related objects (RM):** space objects intentionally released as space debris which served a purpose for the function of a rocket body. Common examples include shrouds and engines.
- **Rocket fragmentation debris (RF):** space objects fragmented or unintentionally released from a rocket body as space debris for which their genesis can be traced back to a unique event. This class includes objects created when a launch vehicle explodes.
- **Rocket debris (RD):** space objects fragmented or unintentionally released from a rocket body as space debris for which the genesis is unclear but orbital or physical properties enable a correlation with a source.

Fig. 2.1 shows the composition of space debris: 59% of the objects orbiting the Earth are fragments generated by collisions or explosions; 16% are retired satellites; 12% are parts of rockets that were used to put the payloads in orbit; 7% are other mission related objects (e.g., PM or RM). Just the 6% are operational satellites. Fig. 2.2 shows a view of the Earth with all the catalogued objects. Orbits are not evenly populated. The LEO region, between 800 and 900 km, is the most crowded area (Fig. 2.3) due to the presence of many remote sensing missions which follow a Sun-synchronous orbit to exploit the stable illumination conditions that favor observations.

## 2.2 The Threat of Space Debris

Space debris represent a threat to operational payloads. Due to the high orbital speed, an impact with a fragment as small as 10cm or less can result in the partial or complete loss of a mission [34]. Accordingly, when a collision warning is received, satellite operators must assess in a timely manner whether a collision avoidance manoeuvre is needed. For example, on Monday 2 July 2018, ESA engineers were

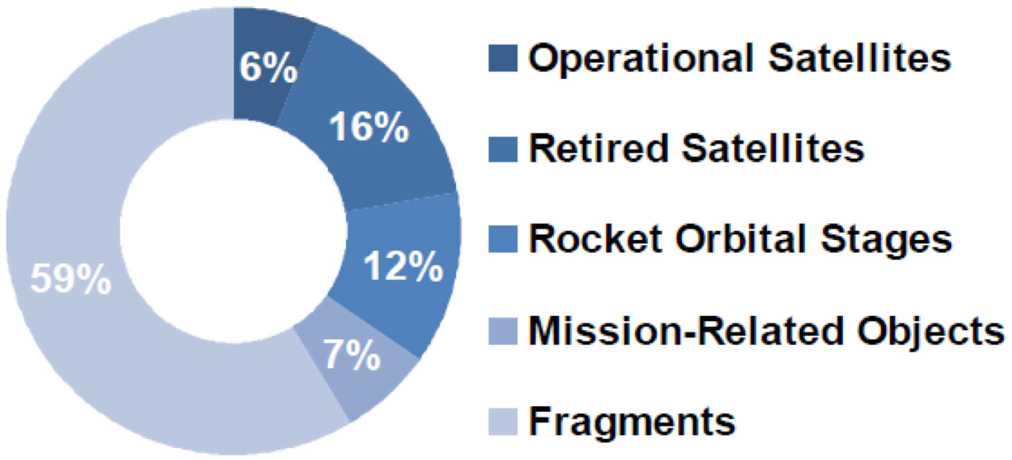

*Figure 2.1: Composition of the catalogued objects*

forced to move the CryoSat-2 satellite to a higher orbit to avoid a piece of debris traveling at 4.1 km/s so as to save the €140-million satellite [53]. However, collision avoidance maneuvers waste fuel that could otherwise be employed for the satellites' main operations. Thus, only collisions above a certain threat threshold are actually avoided. Furthermore, these manoeuvres often require a momentary suspension of the satellites' service, but this can be infeasible because of the mission's constraints [29]. Finally, the evaluated collision risk is usually an underestimation of the real threat since catalogues do not include fragments smaller than 5-10cm. When only partial information on incoming debris is available, additional clues are collected using telescopes shortly before the impact.

Fragments smaller than 1cm could be, in theory, neutralised with shields.[16]. However, fragments between 1cm and 10cm can neither be blocked by shields nor tracked; therefore, they are incredibly dangerous. In fact, McKnight et al. [19] suggested that such small non-trackable objects might become a primary factor in the decrease of space flight safety.

Space debris also pose a threat to people and properties on the ground. When an uncontrolled object re-enters the atmosphere, part of it is destroyed by the heat while between 10% and 40% of its original mass reaches the Earth's surface [39] as fragments. These surviving fragments possess enough energy to severely damage what they hit and they also pollute the environment.

## 2.3 History of Space Debris

The space age began with the launch of Sputnik 1 on October 4, 1957 and, over the years, the number of objects orbiting the Earth has increased dramatically. Fig. 2.5 shows the evolution of the number of catalogued objects in space with colours representing their classes (see Section 2.1). Note that, while the number of payloads and rocket bodies comes from mission designs, the other ones are an underestimation of the space population.

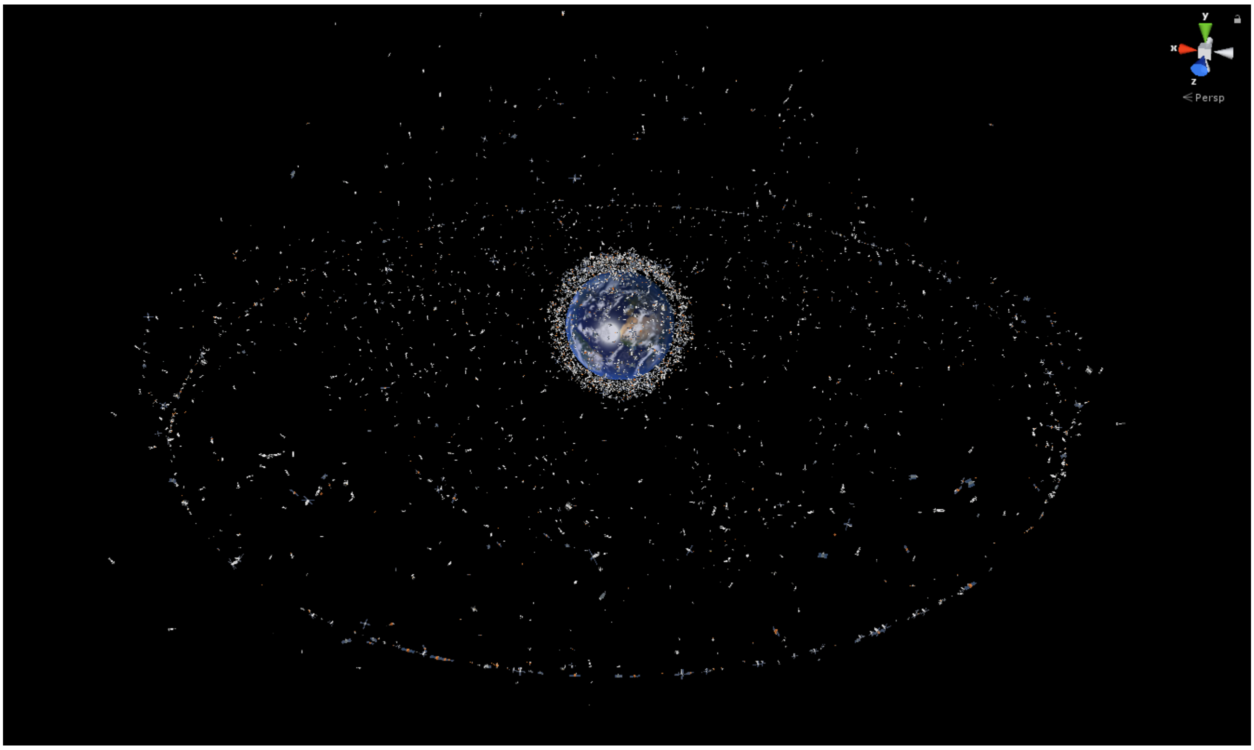

*Figure 2.2: Catalogued objects orbiting around the Earth. While all shown objects are based on actual data, their size is exaggerated with respect to the size of the Earth to make them visible.*

In 1978, Kessler [18] was the first to postulate that collisions and explosions in orbit could lead to a cascade effect and produce a dramatic increment in the number of space debris that would make near-Earth space missions too hazardous to conduct. In 1982, the National Aeronautics and Space Administration (NASA) organised the first conference dedicated to space debris. The following year, the European Space Agency (ESA) held the first workshop on the re-entry of space debris because of the re-entries of Skylab and Cosmos-1402. Nations gathered individually the technical expertise to tackle the problem for most of the 1970s and the 1980s. However, its global nature called for the need of sharing the acquired knowledge at an international level. NASA started multi-lateral meetings between experts that eventually led to the foundation of the Inter-Agency Space Debris Coordination Committee[3] (IADC) in 1993, by the European Space Agency[4] (ESA, Europe), NASA (USA), NASDA (now JAXA, Japan Aerospace Exploration Agency, Japan), and RSA (now Roscomos, Russian Federation). Since its foundation, nine more agencies have joined it: ASI (Italy), CNES (France), CNSA (China), CSA (Canada), DLR (Germany), KARI (South Korea), ISRO (India), NSAU (Ukraine), and UKSA (United Kingdom). IADC is now the major international technical body in the field of space debris [32].

Fragmentation of large, unbroken objects is one of the major factors influencing

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[3] `https://www.iadc-online.org`

[4] `https://www.esa.int/ESA`

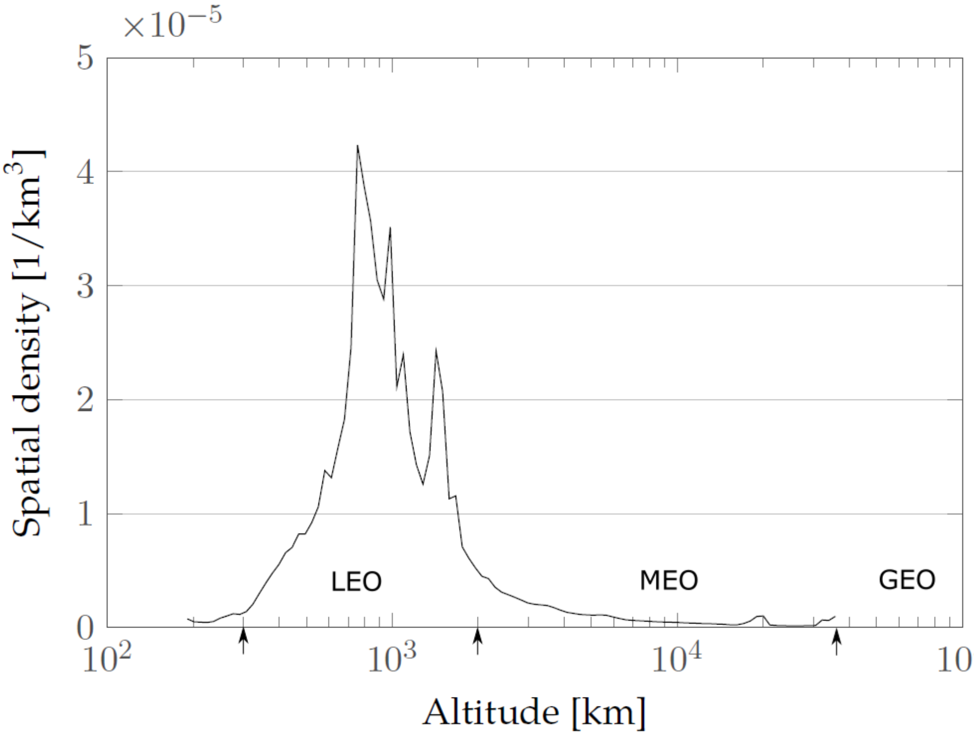

*Figure 2.3: Estimated spatial density of objects larger than 1mm as a function of the altitude, based on the MASTER 2009 population (`https://sdup.esoc.esa.int/web/csdtf`)*

the long-term evolution of the space debris environment [2]. The generated cloud of fragments affects both the orbit in which the event took place and other orbital regimes, as shown in Fig. 2.4.

The spikes in Fig. 2.5 corresponding to years 2007 and 2009 are due to two catastrophic fragmentation events. In 2007, China conducted an anti-satellite test which led to the intentional destruction of the Fengyun-1C. The 880kg satellite split in almost 2000 fragments that increased the spatial density of objects at its fragmentation altitude of more than 60% [41]. The satellite was hit at an altitude of 863 km, where atmospheric drag, which is the only available natural sink mechanism for space debris, is not very effective. Therefore, the generated fragments will remain in orbit for a long time [11]. In 2009 the non-functional satellite Cosmos 2251 crashed into the operational Iridium 33 destroying it and creating more than 2000 new fragments [12]. Since the collision happened at an altitude similar to that of the Chinese missile test, the same problems in terms of the fragment orbital life apply. Because of inaccurate information on the position of the Cosmos, at the moment of the impact the Iridium was being manoeuvred towards it for operation purposes. The collision might have been avoided having the Iridium manoeuvre away from the course of the abandoned spacecraft, but, due to the inaccuracy of the information, the estimated risk of an impact was not decreed high enough. ESA carries out more than 20 satellite manoeuvres a year to avoid collisions with debris. The Chinese anti-satellite test and the Iridium-Cosmos collision are responsible for about half of those manoeuvres [53].

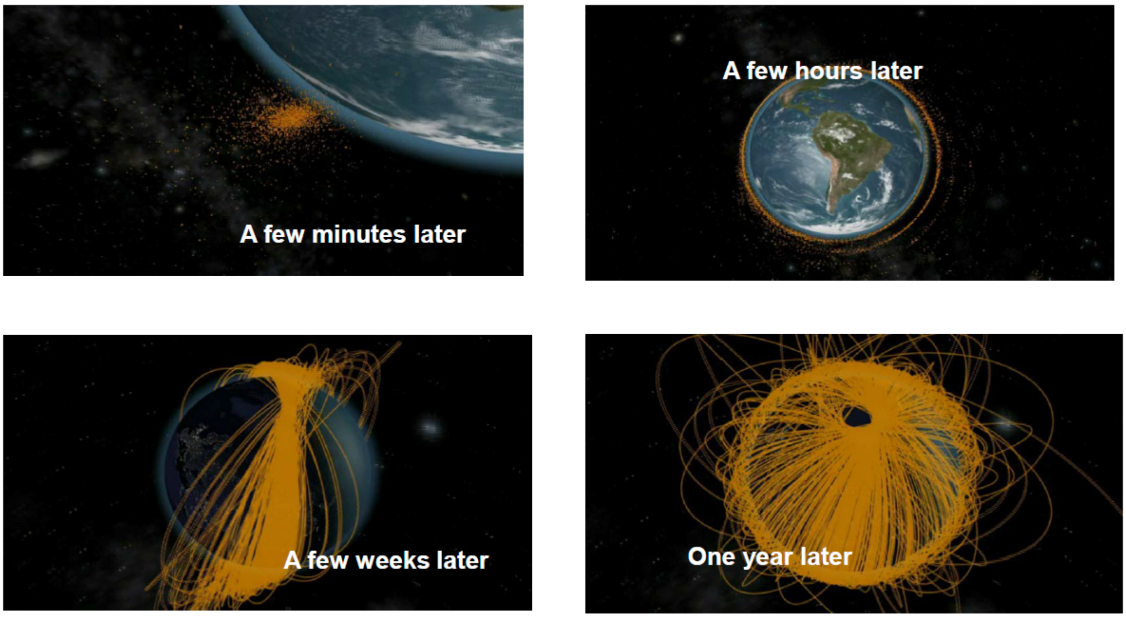

*Figure 2.4: Evolution of a debris cloud generated by a fragmentation event.*

The number of confirmed on-orbit fragmentation events since the beginning of the space age until 2017 is 489. Fig 2.6 shows the number of fragmentation events per year and by what they have been caused. The causes have been classified by ESA as follows [38]:

- **Accidental:** subsystems which showed design flaws ultimately leading to breakups in some cases.
- **Aerodynamics:** a breakup most often caused by an overpressure due to atmospheric drag.
- **Collision:** collision with another object.
- **Deliberate:** all intentional breakup events.
- **Electrical:** most of the events in this category occurred due to an overcharging and subsequent explosion of batteries.
- **Propulsion:** stored energy for non-passivated propulsion-related subsystems might lead to an explosion, for example due to thermal stress.

About 7500 satellites have been sent in orbit since 1957 and only about 1200 are still functioning. There are currently more than 20000 catalogued objects orbiting around the Earth of which only 6% are operational.

## 2.4 Mitigation Measures

Predicting the impact location for long-term re-entry has many uncertainties due to the atmospheric drag and the re-entry time. Short-term predictions (i.e. a few

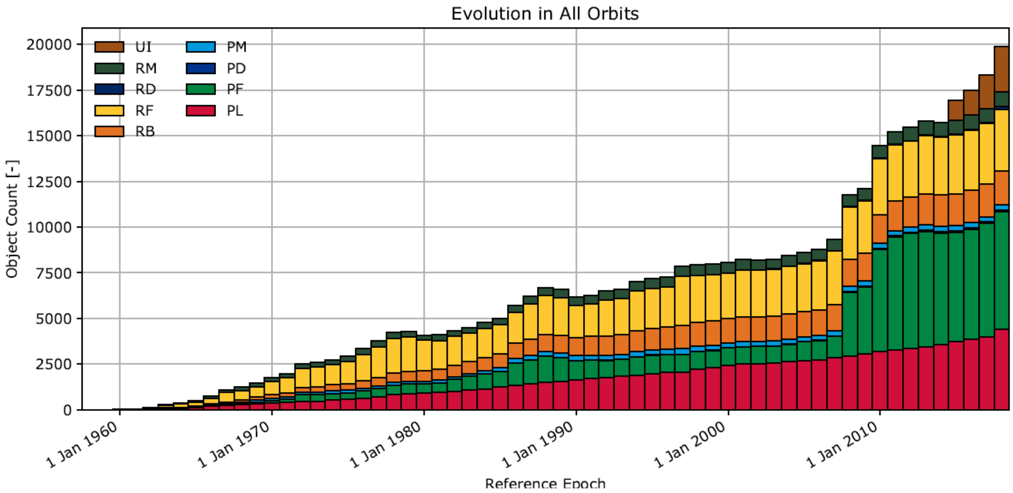

*Figure 2.5: Evolution of the number of catalogued objects orbiting around the Earth since the beginning of the space age. The abbreviations are explained in Section 2.1. (From ESA Space Debris Office, 2017. ESA's Annual Space Environment Report. Produced with the DISCOS Database.* `https://www.sdo.esoc.esa.int/environment_report`*)*

days) allow for a more precise pinpointing of the re-entry path.

As the number of objects in space is ever increasing, scientists are studying innovative ways to tackle the problem. Several approaches can be taken:

- avoidance or protection measures
- Active Debris Removal (ADR)
- passive debris removal

The first approach requires the design of satellites so that they are able to resist impacts by small debris, the selection of less crowded orbits, and the implementation of avoidance manoeuvres.

ADR aims at removing big objects from populated orbits. It is achieved by launching a specialized spacecraft that is able to chase and capture (e.g. with a harpoon or a net) the target object and put it on the path to its destruction. The RemoveDEBRIS project (University of Surrey in Guildford, UK) is experimenting with a net to trap a test satellite and redirect it to an orbit that is due to re-enter the atmosphere. Because of the enormous number of objects in space this kind of active approaches have practical limitations in the long term.

Space debris is a ”self-perpetuating” issue [14] since each mission contributes to increasing the number of debris. Passive approaches aim at limiting the created number of debris. Guidelines to limit the debris proliferation have been developed by international groups such as the Inter-Agency Space Debris Coordination Committee (IADC) since the 2000s. In 2002 IADC published the Space Debris Mitigation Guidelines [32] and presented them to the United Nations Committe on the Peaceful

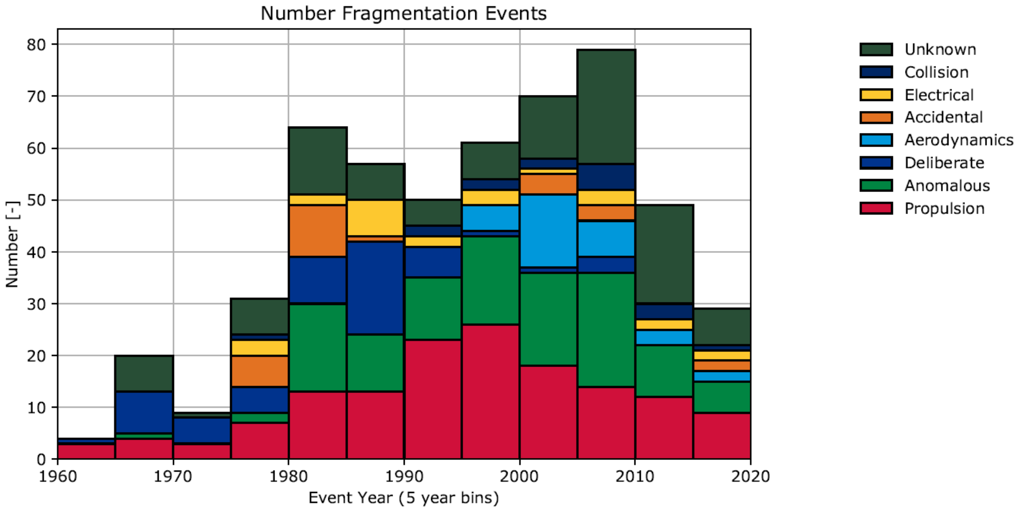

*Figure 2.6: Number of fragmentation events divided per cause*

Uses of Outer Space[5] (UN COPUOS) Scientific and Technical Subcommittee. These guidelines defines the Low Earth Orbit (LEO) and Geostationary Orbit (GEO) regions as protected and therefore should be cleansed at the end of a mission. They also list some requirements to ensure the sustainability of future space activities. In particular, the guidelines include:

- preventing the release of mission related objects
- removing leftover fuel or other pressurized material from rocket bodies after the injection in orbit (*rocket passivation*) and from satellites at the end of their lifetime
- lowering satellites in LEO to have them burn in the atmosphere within 25 years of their dismissal
- moving GEO satellites to ”graveyard” orbits at the end of their life cycle where they can not interfere with operational spacecraft
- performing collision avoidance
- upon re-entry, the risk of causing casualty on ground shall not exceed $10^{-4}$, for both controlled and uncontrolled re-entry

The guidelines are not binding and thus it is up to individual nations, operators and manufacturers to comply with them. The 25-years rule, for example, has been followed by only about half of the missions [46]. Holger Krag, head of ESA’s space debris office in Darmstadt, Germany, is worried that the companies that are planning to send constellations of satellites in orbit (e.g., Boeing, OneWeb, SpaceX[6]),

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[5] `https://en.wikipedia.org/wiki/United_Nations_Committee_on_the_Peaceful_Uses_of_Outer_Space`

[6] `https://spacenews.com/divining-what-the-stars-hold-in-store-for-broadband-megaconstellations/`

despite their best intentions, might not abide to the rule for different circumstances, bankruptcy for one [53].

Astrodynamicist Aaron Rosengren is studying passive approaches that exploit the gravitational pulls of the Sun and the Moon, also called gravitational resonances, to direct the satellites towards orbits that will lead to their destruction. In particular, the idea was born when he was working on the end of life of MEO (Medium Earth Orbit) satellites. MEO orbits span from the end of the Low Earth Orbits (LEO, 2000 km of altitude) to the beginning of the Geostationary Orbits (GEO, 35000 km of altitude). While GEO satellites can be moved in "graveyard" orbits, MEO satellite trajectories suffer too much from gravitational resonances that make them unstable over the long term. By tweaking these trajectories, MEO satellites can be put on orbits that finally lead to the atmosphere and, consequently, to their doom. Rosengren calls this approach *passive disposal through resonance and instabilities* and it has been tested on the INTEGRAL $\gamma$-ray space telescope that is now due to re-enter the atmosphere in 2029 instead of decades later.

# Chapter 3

# Virtual, Augmented, and Mixed Reality

This chapter presents the definitions of Virtual, Augmented, and Mixed Reality, their history and the underlying technologies.

## 3.1 Virtual Reality

Virtual Reality (VR) is often described as a three-dimensional, interactive, computer-generated environment in which the user, through closed visors or goggles, is totally immersed [31]. Such synthetic environment completely blocks out and replaces the real one to trick users' brains into believing they are somewhere else. Interaction with the digital world may or may not mimic the one we are used to have with our surroundings, depending on the aim of the experience itself. Immersion is mainly achieved through the sense of sight, although, ideally, it would require also the simulation of the stimuli perceived by the other senses. However, this definition limits the scope of VR to computer-generated experiences. The concept of *presence* is required to extend its applicability beyond the sole hardware. Presence refers to one's perception of her surroundings mediated by both automatic and controlled mental processes [26], and not to the surroundings as they exist in the physical world. The perceptual factors that contribute to this feeling include input from sensory channels as well as other mental processes that assimilate incoming sensory data with current concerns and past experiences [25]. When a person's perception is mediated, she is forced to perceive two distinct environments at the same time: the physical environment, and the one presented via the medium. *Telepresence* is the extent to which a person experiences a sense of presence in a mediated environment [27]. There are no restrictions on the type of mediated environment. It can be real, spatially or temporally distant, or computer-generated. VR can now be defined, without any reference to the underlying technology, as a real or simulated environment in which a perceiver experiences telepresence [27].

*Figure 3.1: An extract from Franz Roubaud's panoramic painting "Battle of Borodino".*

### 3.1.1 History of Virtual Reality

The first experiments with Virtual Reality (VR) date back to long before the advent of digital computing. Panoramic paintings from the 19th century aimed at filling the viewer's field of vision to give the impression of being immersed in the portrayed scene [1]. In 1838, Charles Wheatstone proved that the brain merges the two-dimensional images from each eye to give us a three-dimensional sense of sight. This principle, called stereoscopic view, was at the basis of the invention of the stereoscope by the same Wheatstone, a device that allowed users to see two stereoscopic images and gave the illusion of looking at a larger 3D image, and eventually led to the creation of the popular View-Master stereoscope (Fig. 3.2) in 1938. In 1891, Thomas Edison and William Dickson invented the Kinetoscope. It sent a piece of film between a lens and a light bulb so that the viewer, peering through a peephole, could see images at 46 *frames per second* (fps).

VR allows people to experience in a safe way situations that might be too dangerous or difficult to reproduce in real life. For this reason, in 1929, Link developed the first electromechanical flight simulator that was able to simulate plane movements and external disturbances such as turbulences. The US military bought several of these devices and extensively exploited them during World War II to train pilots.

*Figure 3.2: The View-Master stereoscope*

In the 1950s, cinematographer Morton Heilig developed the Sensorama, an arcade-style theatre cabinet to fully immerse the viewer in the movie (Fig. 3.3). It was equipped with a stereoscopic 3D display as well as stereo speakers, but its true novelty was that it could stimulate all the other senses thanks to the vibrating seat, fans, and smell generator.

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[1] `https://www.vrs.org.uk/virtual-reality/what-is-virtual-reality.html`

The cinematographer produced several short films for its debut, one of which featured a motorcycle ride through the streets of New York with the smell of hot dog stalls. Morton Heilig also developed the first Head-Mounted Display (HMD), the Telesphere Mask, in 1960. It was meant to show 3D movies with 3D stereoscopic images, widescreen vision and stereo sound. It offered no interactivity and lacked motion tracking, nevertheless it helped lay the basis for future VR developments. In 1961, Philco engineers developed the Headsight, an HMD that allowed remote viewing of dangerous situations by the military. Head rotations were tracked and reflected on the rotation of the remote camera used to look around in the environment.

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*Figure 3.3: Morton Heilig's Sensorama*

Until 1965, flight simulators were the only VR systems allowing some kind of interaction. However, to achieve a more complete sense of telepresence, interaction with the surroundings is of paramount importance. At that time Ivan Sutherland presented his vision of what he called *The Ultimate Display* [49], a simulation that would feel so authentic it could be mistaken for reality. Ivan Sutherland also created the first prototype of computer-generated Augmented and Virtual Reality experience at Harvard University in 1968 (Fig. 3.9). It was named *The Sword of Damocles* and used an Optical See-Through (OST) Head-Mounted Display with a ceiling mounted tracking system to display simple wire-frame graphics [50]. The system tracked head movements and made virtual objects appear fixed in the real world.

In 1977, scientists at the Electronic Visualisation Laboratory of the University of Illinois developed the first wired glove, the Sayre Glove, that could turn finger move-

Figure 3.4: An example of CAVE systems

ments in electrical signals [48]. The following years, Thomas Zimmerman and Jaron Lanier worked to improve the Sayre Glove using optical, ultrasonic and magnetic sensors. This led to the creation of the Power Glove and the Data Glove. The Power Glove's design was used as a basis for Nintendo's Power Glove[2], commercialised in 1989 as an accessory for the Nintendo Entertainment System[3].

Jaron Lanier, founder of the Visual Programming Lab (VPL), coined the term Virtual Reality in 1987. His company was the first to sell VR glasses and gloves, among which appeared the aforementioned Data Glove and the EyePhone HMD. VPL also cooperated with NASA in the development of the Virtual Interface Environment Workstation (VIEW), a HMD that could show either a computer-generated environment or a real one relayed from a remote camera. It also featured input from the Data Glove and the Data Suit, a full body outfit used to track the movement of the limbs.

In 1992, Chicago Electronic Visualisation Laboratory developed a VR system called Cave Automatic Virtual Environment (CAVE) [17]. Such system adopted a different approach, with respect to HMDs, in showing the digital environment to the user. In this case, the user is placed in a room that has screens instead of walls (Fig. 3.4). Images of the environment are then projected on those screens to create the feeling of immersion.

In the early 1990s VR started being exploited also for entertainment purposes. Although the technology was still too costly for the majority of consumers, com-

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[2] `https://en.wikipedia.org/wiki/Power_Glove`

[3] `https://en.wikipedia.org/wiki/Nintendo_Entertainment_System`

panies like The Virtuality Group presented a series of arcade games and machines equipped with real time VR experiences (Fig. 3.5) that, in some cases, also offered a multi-player variant.

In the same period, SEGA[4] attempted to launch a VR HMD to be used with their gaming console, Genesis[5]. The HMD was intended for a wider audience, with its price being about $200 at the time. It was equipped with stereo headphones, LCD displays and sensors for tracking head movement. However, the development went on for a couple of years before being interrupted, and the device was never released. Nintendo[6] too ventured in the direction of a widely affordable device with the release of the Virtual Boy in 1995 (Fig. 3.6). It was a portable gaming console with a stereoscopic display, shipped along with a handheld controller. Despite the promises of the commercials, the quality of the graphic was poor since it could only show red images on a black background. Moreover, it forced the player to maintain an uncomfortable position while playing. For these reasons it resulted in a failure, with sale and production interrupted the following year.

*Figure 3.5: VR arcade machines developed by the Virtuality Group*

*Figure 3.6: Nintendo Virtual Boy*

The $21^{st}$ century has seen the development of VR devices and applications grow at an unprecedented rate. The increasingly powerful and ever smaller mobile devices and the steady decrease in their prices have granted access to these technologies to a wider audience, composed both by enthusiasts and researchers. In 2010, 18-year-old Palmer Luckey designed the first prototype of the Oculus Rift (Fig. 3.7), a new, lightweight, affordable HMD. Two years later, his Kickstarter project raised $2.4 million and, in 2014, the company was purchased by Facebook for $2 billion. Al-

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[4] `https://www.sega.com/`

[5] `https://en.wikipedia.org/wiki/Sega_Genesis`

[6] `https://www.nintendo.com/`

though the HMD was only capable of rotational tracking, it provided a 90-degree FOV that no other headset possessed at the time. Since then, all the major technology industries have entered the market, along with companies specialised in the VR sector. Nowadays, dozens of HMDs and VR applications are available on the markets. Fig. 3.8 shows some of the available commercial HMDs.

### 3.1.2 Head-Mounted Displays

Head-Mounted Displays are the most widely used displays for VR. They rely on the same principle of the stereoscope, showing two slightly different two-dimensional images to give the user a sense of depth [42]. Displays are based on LCD or OLED technologies. Since the cumbersome Sword of Damocles, the first HMD designed for an interactive experience, headsets have evolved becoming lightweight and portable. They can be either wired or mobile and can track only head rotations or both rotations and movements. Among the same category, HMDs also differentiate from one another because of their refresh rate, latency and field of view.

*Figure 3.7: First prototype of Oculus Rift.*

Mobile HMDs are wireless and can be used without a PC. They usually consist of a simple case for a smartphone, which provides the actual display and the processing power. The phone is placed at a fixed distance from the lenses that are present in the box. Smartphone-based HMDs track only the rotation of the head and this makes them well suited for applications in which the user either views the surroundings from a single point (like 360° movies or panoramas), or navigates the environment with her gaze [1]. They are the cheapest HMDs and, like with Google Cardboard[7],

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[7] `https://vr.google.com/cardboard/`

*Figure 3.8: Some available commercial VR HMDs. From left to right: Samsung's GearVR, the latest version of Oculus Rift, PlayStationVR, HTC Vive*

may not even have a band to make it hold onto the head. A more refined, but also more costly, alternative to Google Cardboard is Samsung GearVR[8], which is compatible only with Samsung smartphones. It features an ergonomic headband and an additional touchpad on the side of the case. Recently, mobile HMDs not based on smartphones have started to appear. Oculus Go[9] is an example. They have a computational power similar to that of high-end smartphones but offer a wider choice in terms of input devices.

Wired HMDs, as the name implies, are tethered to a PC or, as in the case of PlayStationVR[10], to a gaming console. They have the advantage of allowing more complex and captivating experiences than those supported by smartphone-based HMDs but require powerful enough PCs. Moreover, the cable proves to be a nuisance on which it is easy to trip while wearing the headset. However, they have the advantage of being able to support a wider range of input devices and interaction patterns.

### 3.1.3 Input Devices

Input devices let the user interact with the virtual world. The early application prototypes for HMDs exploited mouse and keyboard or game controllers for this purpose. However, they drastically reduced the sense of presence in the virtual environment since they are difficult to use when the player cannot see them. The next paragraphs describe the most frequently used input devices in VR.

Controllers specifically designed to be used with HMDs are the most common form of input for VR. They are hand worn and equipped with buttons, joysticks, or touchpads. They usually come in pairs, one per hand, and provide a 6 Degrees of Freedom (DOF) hand tracking. Additionally, they may have haptic feedback and gesture recognition technologies [4].

Navigation devices are used to allow the user to wander in virtual environments. They must give the impression of moving through an endless space [4]. Some examples are the Omnidirectional Treadmills (ODTs), which support movement in a two-dimensional plane, and devices that allow walking in place or while sitting. ODTs for VR were explored by Iwata et el. [24] in the late 1990s.

Several other input devices providing different functionalities are available, such as Leap Motion, which, thanks to its infrared cameras, tracks the skeletal movements of the hand; gloves for hand tracking and gesture recognition; suits that rely on different types of sensors to provide full body tracking.

## 3.2 Augmented Reality

Augmented Reality (AR) aims at enhancing users' perception of and interaction with a real environment by superimposing virtual information on users' view of

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[8] `https://www.samsung.com/global/galaxy/gear-vr/`

[9] `https://www.oculus.com/go/`

[10] `https://www.playstation.com/en-gb/explore/playstation-vr/`

their surroundings. Unlike VR, in which the user is immersed in a completely virtual world, AR supplements reality with virtual objects that appear to coexist with it. AR is an effort by scientists and engineers to make computer interfaces invisible [44] [8]. Azuma [7] provides a commonly accepted definition of AR as a technology with the following characteristics: (i) it combines real and virtual objects in a real environment; (ii) it is interactive in real time; (iii) it registers (aligns) real and virtual objects with each other. This definition does not limit AR to specific display technologies, like Head-Mounted Displays (HMDs), nor to the sense of sight. Some AR systems also provide an audio or haptic experience like [47] and [40]. Robinett [45] mused on the potential of AR for applications that require displaying information not directly available or detectable by human senses. By making that information visible through virtual objects, users could be helped in performing real-world tasks [10].

In his 1997 survey, Azuma [7] extended AR's definition to include also systems that have the potential to remove objects from the real environment. However, this was defined by Mann [33] as Mediated Reality and it encompasses technologies that function as intermediary between the user and the surrounding environment, modifying, augmenting or removing parts of it. Some examples of this are the eyeglasses that reverse images left to right [20] and the ones that filter out advertisements.[11]

### 3.2.1 History of AR

Although AR technologies we are used to are rather new, the concept itself dates back to many years before. L. Frank Baum, the author of *The Wizard of Oz*, in his 1901 illustrated novel *The Master Key*, described a pair of glasses that allowed the wearer to see marks on people's foreheads indicating their true nature[12]. However, the first prototype of computer generated AR experience was created only in 1968, by Ivan Sutherland at Harvard University (Fig. 3.9). It was named *The Sword of Damocles* and used an Optical See-Through (OST) HMD with a ceiling mounted tracking system to display simple wireframe graphics [50].

In the 1970s and 1980s research in AR was mainly brought on in military and government facilities. As an example, Thomas Furness of Wright Pattern Air Force worked on the SuperCockpit project [23], a system envisioned as an innovative way to present complex flight details to pilots without overloading them with information.

During the 1990s, several academic research groups studied some key technologies to enable AR like See-Through (ST) HMDs [28, 3], registration and tracking [5, 6], and also applications in a variety of fields. The term *Augmented Reality* was coined in 1992 by Boeing researchers Dave Mizell and Tom Caudell [13] who developed an AR system to improve workers' efficiency in creating wire harness bundles. The system exploited visual cues to pinpoint which wires had to be bundled together. The 1990s also brought significant advancements in wearable computing, although these systems were still quite bulky due to the size and weight of the necessary

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[11] `https://motherboard.vice.com/en_us/article/xw337w/these-screen-blocking-glasses-are-ad-blocker`

[12] `http://www.historyofinformation.com/expanded.php?id=4698`

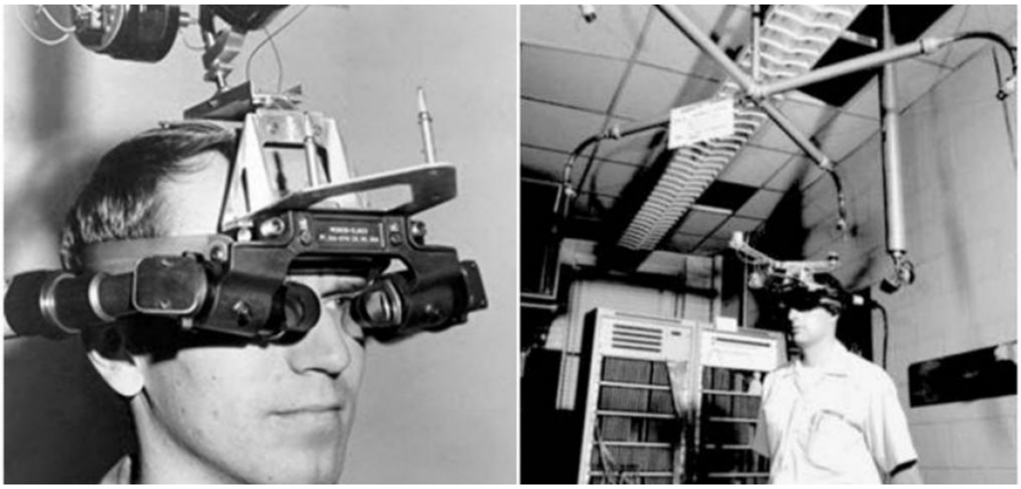

Figure 3.9: Sutherland's Sword of Damocles

hardware. Nonetheless, the first outdoor AR systems started to appear [21], [51], as well as the world's first outdoor AR game, ARQuake, in 2000. It was an AR version of the popular Quake game by id Software[13] and the system's overall weight was 16 kg (Fig. 3.10).

In 1999, the ARToolkit[14] tracking library was developed by Kato and Billinghurst [30] and was released as open source software the following year. It provided essential functionalities that consistently eased the making of new AR applications and thus became one of the most used AR tracking libraries.

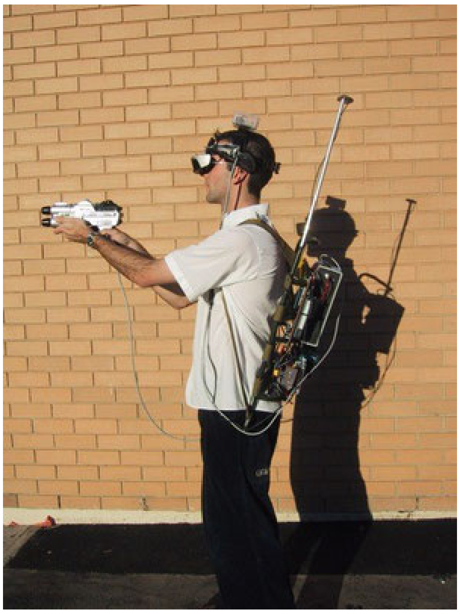

Figure 3.10: Person wearing the 16kg equipment needed to play ARQuake.

The first AR conference was held in 1998 in San Francisco and was the IEEE/ACM International Workshop on Augmented Reality (IWAR). It was followed by the International Symposium on Mixed Reality (ISMR) and the International Symposium on Augmented Reality (ISAR) which, in 2002, merged to give birth to the International Symposium on Mixed and Augmented Reality (ISMAR)[15], today's major symposium for industry and research on these topics.

With the beginning of the new millennium came the possibility for millions of people to have access to the technology for experiencing AR. In 2003, handheld devices were becoming increasingly powerful, up to the point that Wagner et al. [52] developed the first self contained handheld AR application, and, in 2004, Mohring and Bimber [37] showcased the first experience

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[13] `https://www.idsoftware.com/?/age_gate`

[14] `artoolkit.org`

[15] `https://www.ismar2018.org/main_about/index.html`

*Figure 3.11: Google Glasses*

based on a mobile phone. Soon after, the ARToolkit was ported to mobile phones [22]. In the same years, recreational applications exploiting AR started spreading more and more. Theme parks uncovered AR enhanced rides, such as the AR Adventure Game in Guandong Science and Technology Center (China), and Sony PlayStation 3 released in October 2007 the game *The eye of judgement* which featured card-based battles and exploited the PS-3 camera and a derivative of Sony's original CyberCode[16] to bring to life AR characters on top of physical playing cards. In 2008 Adobe[17] added camera support to Flash[18] and a pair of Japanese developers ported the ARToolkit library to Flash, giving birth to the FLARToolkit. This opened the way for the creation of web-based AR experiences that could be run on everyone's browsers. Furthermore, with the release of the iPhone[19] in 2007 and that of the first Android[20] phone in late 2008, AR developers had the availability of phones it was easy to develop for, possessed enough computational power to run real time tracking and render 3D graphics, and provided a wider range of sensors. Last but not least, AR was beginning to be used in advertising thanks to its capability of offering captivating experiences to possible customers. In 2014 Google released its Google Glass (Fig. 3.11), Android-based AR eyeglasses that could project clear images on a display in front of the user's eye [36]. They were designed to be used mostly hands free and, to that purpose, integrated a microphone for the voice commands. They were also equipped with a speaker and a camera and this led to severe criticism due to privacy concerns. They were retired from the market in 2015 to be released again in Enterprise Edition in 2017 for a more restricted audience. The biggest AR game for smartphones of the recent years has been Pokémon Go[21], with a profit of 2 billion dollars and more than 500 millions of downloads since its re-

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[16] `https://www.sonycsl.co.jp/tokyo/320/`
[17] `https://www.adobe.com/`
[18] `https://en.wikipedia.org/wiki/Adobe_Flash`
[19] `https://www.apple.com/iphone/`
[20] `https://www.android.com/`
[21] `https://www.pokemongo.com/it-it/`

*Figure 3.12: Player trying to catch Pokémons embedded in their surroundings in Pokémon Go*

lease in July 2016. The game allows players to hunt for Pokémons in the real world thanks to the GPS localisation and see them embedded in their surroundings as in Fig. 3.12.

In June 2017 Apple released the ARKit, a framework to help developers create AR experiences for iOS that also supported the main game engines like Unity3D[22] and Unreal Engine[23]. The following year Google released ARCore, a Software Development Kit (SDK) to develop AR applications both for Android and iOS devices[24] that also supports the same game engines. The release of ARCore decreed the end of Project Tango, a previous project by Google aimed at giving smartphones full spatial awareness. With the latest update, Pokémon Go makes use of ARCore functionalities for a better positioning of Pokémons in the real world and to give them awareness of the position and velocity of the player.

### 3.2.2 Registration and tracking

Before rendering a scene, AR applications need to know how and where to position the virtual objects in the real world relatively to the user's viewpoint, to avoid disrupting the feeling that the two worlds are coexisting. This is known as the registration problem. In AR applications, registration must be as accurate as possible since human eyes are able to perceive a mismatch between real and virtual graphics of even a few millimeters. Virtual environments, on the other hand, have looser requirements in terms of positioning accuracy.

Registration errors can be static or dynamic. Static errors cause a mismatch in the alignment even when the user's viewpoint and the objects in the environment

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[22] `https://unity3d.com/`

[23] `https://www.unrealengine.com/en-US/what-is-unreal-engine-4`

[24] `https://developers.google.com/ar/discover/supported-devices`

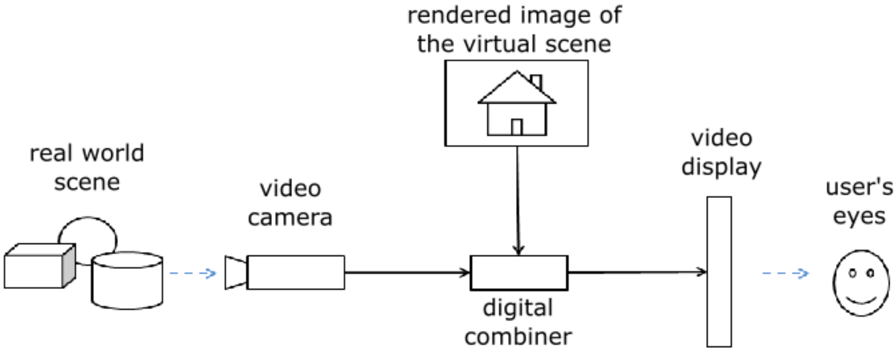

*Figure 3.13: Conceptual diagram of the structure of a Video See-Through AR display (taken from [8]).*

are not moving. Dynamic errors, on the other hand, affect the registration when either the user's viewpoint or the objects in the environment are moving.

Tracking allows to detect the viewer's pose (position and orientation) relative to the environment and that of the target objects. This is crucial in order to correctly register virtual content in the real world. Several tracking techniques exist and there is no single best solution. The choice depends largely on the problem at hand.

Sensor based tracking relies on sensors of different types (magnetic, inertial, GPS, acoustic etc...) to detect the viewer's pose. Each type of sensor has its advantages and disadvantages.

Vision based tracking methods exploit optical sensors such as cameras to determine the viewer's pose. Their popularity has risen in the recent years thanks to the increased availability of mobile devices. Such devices are equipped with both a camera and a screen thus providing an ideal platform for AR. Optical sensors can be divided in three categories: infrared sensors, visible light sensors, and 3D structure sensors. Visible light sensors are the most commonly used since suitable cameras can be found in a wide variety of devices, from laptops to smartphones. Tracking and registration methods based on them can make use of artificial landmarks located in the environment to facilitate the process.

Hybrid tracking methods merge data coming from different sensors to improve the accuracy and take care of the weaknesses of the single techniques.

### 3.2.3 Displays

Displays for AR applications can be divided in three categories depending on how they combine the real and virtual worlds: Video See-Through (VST), Optical See-Through (OST), and projection based.

VST displays embed the virtual content in videos of the real world. Fig. 3.13 shows a conceptual diagram of their functioning. First, a video camera captures an image of the real world. Then, a digital combiner composes the final image to be presented on the display by merging the rendered image of the virtual scene with the one coming from the camera. The camera is usually attached on the back of the display facing towards the real world scene to create the illusion of "seeing through" the display. Depth information can be added to the captured image of the environment to correctly perform occlusion between real and virtual objects. The biggest problems arising with the use of this kind of displays are: limited resolution, distortion, delay, eye displacement, and the necessity of more computational power to compose the final image.

OST displays employ optical systems to compose the final image containing both real and virtual objects. As shown in Fig. 3.14, the user directly sees the real world through partially transmissive optical combiners. Such combiners, however, are also partially reflective so that the virtual images coming from the monitor can be reflected towards the user's eyes. These systems don't suffer from the problems of VST displays since they do not need to digitise the real world scene, but they make accurate registration more difficult to achieve. Furthermore, due to the nature of optical combiners, the amount of light that reaches the user's eyes is reduced and virtual images appear semi-transparent, never fully occluding the real world.

OST and VST displays expose the final image at the display's site. On the other hand, projection based displays overlay virtual images directly on the surface of physical objects. This is achieved thanks to projectors that can be either fixed (e.g., mounted on a ceiling or a wall) or mobile (e.g., attached to the user's head). The target physical objects must have an adequate surface onto which images can be projected. Projection based displays suffer heavily from unsuitable lightning conditions and shadows created by other nearby objects. Furthermore, achieving a correct occlusion when other physical objects are placed between the projector and the target objects is more difficult than with OST or VST displays.

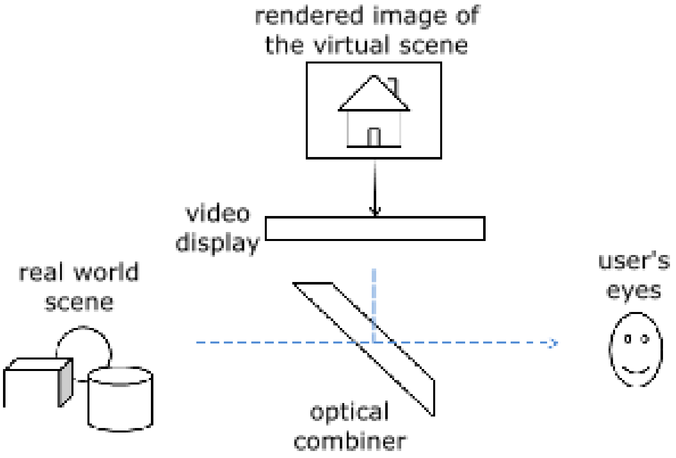

*Figure 3.14: Conceptual diagram of the structure of an Optical See-Through AR display (taken from [8]).*

## 3.3 Mixed Reality

Mixed Reality (MR) was originally introduced as a term by Milgram and Kishino [35] to define technologies that involve the merging of real and virtual worlds. In particular, these technologies encompass what they refer to as the Reality-Virtuality continuum (Fig 3.15). On the left side of the continuum lies an environment composed solely by real objects, while on the opposite side the environment is made purely of virtual objects [43]. The former includes the cases in which the user is viewing a real-world scene in person or through a window-like display. The latter

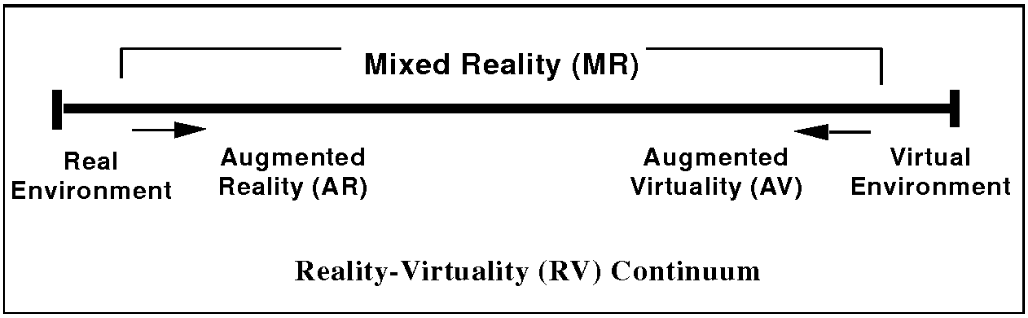

*Figure 3.15: The Reality-Virtuality Continuum*

may refer to a generic computer graphic simulation or to a Virtual Reality (VR) experience, in which the user, through closed visors or goggles, is immersed in a completely synthetic world that blocks out and replaces the real one. The interaction with the digital world may mimic the one we are used to have with our surroundings or not, depending on the aim of the experience itself. MR is placed between these two extremes, blending real and virtual worlds in various proportions.

When the observed environment is mainly virtual, thus lying near the right end of the continuum, but is augmented with real imaging data, it is referred to as an Augmented Virtuality (AV) environment. On the other hand, Augmented Reality (AR) allows to experience the real world with computer generated content added onto or embedded into it. Since its introduction in 1994, which mainly concerned displays, Mixed Reality has expanded to include also environmental input (e.g. head tracking, spatial mapping etc.), spatial sound and location.[25]

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[25] `https://docs.microsoft.com/en-us/windows/mixed-reality/mixed-reality`

# Chapter 4

# A Mixed Reality Experience for Space Debris

This chapter overviews the educational application we designed to raise awareness about the space debris problem and to explain the threat it poses to current and future space missions. Our application targets both people with some background knowledge about space missions (such as aerospace engineering students) and people with other backgrounds.

## 4.1 Educational Applications for Space Exploration

There are several applications for Virtual and Augmented Reality that let players explore the galaxy (e.g., Galaxy Explorer[1]), the Solar System (e.g., VR Space[2]), be an astronaut (e.g., Astronaut VR[3]), or pilot a spaceship (e.g., EVE: Valkyrie - Warzone[4]). However, these applications mainly focus on providing a visually captivating experience and do not try to achieve an accurate scientific simulation. European Space Agency (ESA) released a wide variety of multimedia products to explain some key concept of space exploration and also debris that are freely available.[5] Their contents, however, are not interactive. Our aims included to achieve an accurate scientific simulation and compensate for the lack of interactivity of the existing products from ESA.

## 4.2 Objective and Requirements

Our objective was to design, implement, and validate an educational mixed reality application to let people understand the problem of space debris. The application

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[1] `https://www.microsoft.com/en-us/p/galaxy-explorer/9nblggh4q4jg?activetab=pivot:overviewtab`

[2] `https://play.google.com/store/apps/details?id=com.bce.VR&hl=en_US`

[3] `http://astronaut-vr.com/`

[4] `https://store.steampowered.com/app/688480/EVE_Valkyrie__Warzone/`

[5] `https://www.esa.int/spaceinvideos/Videos/2017/04/Space_debris_2017_-_a_journey_to_Earth`

had to support the lectures of the "Orbital Mechanics" course for aerospace engineering and also be used for dissemination to a general audience. We organized several meetings with experts from the department of aerospace engineering at Politecnico di Milano to identify the requirements for the underlying scientific simulation and the structure of the overall experience. At the end, six requirements were identified. First and foremost, the application had to effectively convey the entity of the space debris problem and show why it poses a threat to current and future space missions. Second, it had to implement a story-driven experience and a fully exploratory experience. It had to allow the exploration of the space population orbiting the Earth by selecting different types objects (payloads, fragments, rocket bodies) and trajectories. It also had to support different Augmented Reality (AR) and Virtual Reality (VR) headsets and their interaction patterns. It had to run smoothly on wireless, low cost hardware with limited processing power. Finally, it had to provide a teaching and a student mode to support lectures. In this thesis, we focused on the first five requirements and left the class support for future development.

## 4.3 Design of the Experience

The experience we were asked to provide had to be both a tool to increase the awareness on the space debris problem and a support for the "Orbital Mechanics" lectures. Accordingly, we structured it in two parts: a Story Mode and an Exploration Mode. The former focuses on presenting the space debris problem to a general audience. The latter allows to freely explore the near-Earth space to support the lectures. Each section is self-contained and can be experienced without the need to undergo also the other part.

### 4.3.1 The Story Mode

The story part of the experience has been designed in order to explain the space debris problem to an audience with no background knowledge in the field and give other general clues about the orbits of the satellites around the Earth. We designed two different approaches: the first one places users in a space station control room where they can only read space debris information displayed on terminals, the other one is set in space and allows users to interactively progress in the narration.

**Spaceship Control Room** In the first approach, the user finds herself in the middle of the control room of a spaceship. The point of view is fixed allowing only head rotations to look around. As shown in Fig. 4.1, the user is surrounded by terminals each displaying information regarding the space debris problem. At the beginning, all the screens are black and they switch on one at a time from left to right. After the last terminal is turned on, the launch door appears behind the user. It contains a Launch button, a clue saying to click it to start the experience, and an image highlighting which controller's button has to be pressed in order to start. The door was placed behind the user because, ideally, she should follow the

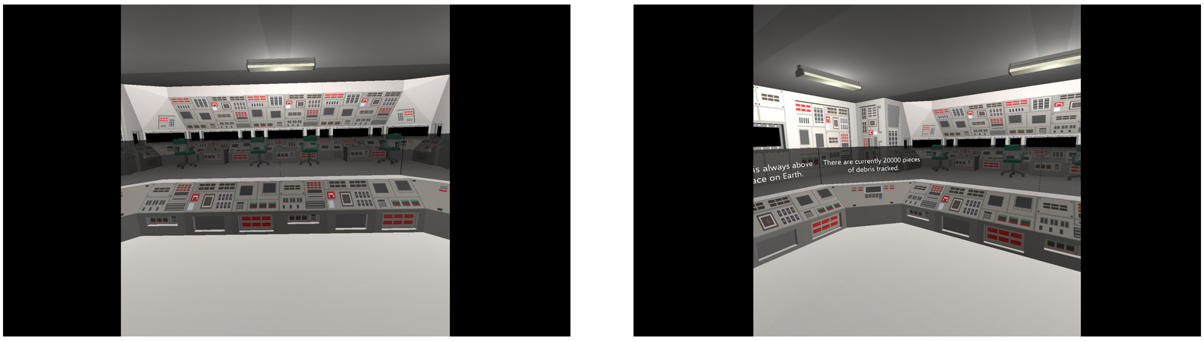

*Figure 4.1: The spaceship's control room from the user's point of view right after entering the scene (left). The surrounding black screens are switched on in turn from left to right and each one displays a sentence regarding the space debris problem (right).*

screens switching on with her gaze so that, after the last one turned on, she would be looking in the right direction to see the panel appear. However, after an initial set of trials with people visiting MeetMeTonight[6] 2018, we discovered that people entering the control room were awed by the setting and would start looking around randomly. After a while, they would see the sentences on the screens in front of them but they never turned enough to see the exit panel, so they asked for directions not knowing how to continue the experience. This problem might be solved with the use of sound clues, which was forbidden at MeetMeTonight because of the event's regulations. Furthermore, we also found out that people actually saw the displayed information but only few stopped to read them, making this part of the experience fruitless.

After launching, users were brought to an overall view of the Solar System. Here, the only available interaction was to click on the Earth to proceed to the tutorial. This limitation was due to the scene being intended as a brief introduction providing a glimpse of the Solar System as a whole, as required by the experts from the aerospace engineering department of Politecnico di Milano.

**Story in Space** The second approach we designed places users directly in space with informative screens appearing right in front of them, as shown in Fig. 4.2. This solution has been devised in order to avoid as much as possible the problem of people skipping such information. It has also been slightly expanded with respect to the control room to include information on the satellites orbiting around the Earth and the history of space debris. At the beginning, users find themselves in space, facing the Earth, and only the International Space Station (ISS)[7] is visible (Fig. 4.2). Satellites and debris are added progressively as the narration goes on, to avoid distracting the user from the story. The only allowed interaction with the environment is to progress with the narration. In order to do so, the user can press a button on the controller or ask an external person (if available) to do it with the keyboard. As in the spaceship's control room, the point of view is fixed so that only

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[6] `http://www.meetmetonight.it/`

[7] `https://en.wikipedia.org/wiki/International_Space_Station`

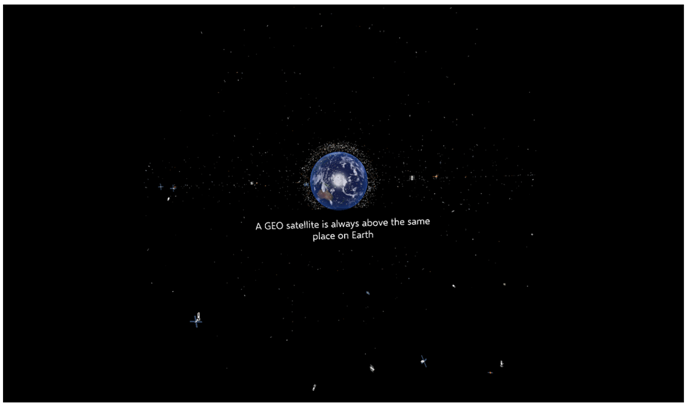
ISS is the only place in space where there are humans

*Figure 4.2: The beginning of the Story Mode set in space. The user starts facing the Earth and informative screens appear in front of her.*

head rotations to look around are allowed. However, in this case, the user's position changes as the narration progresses to offer a better view on the satellites orbiting at different distances from the Earth, as shown in Fig. 4.3.

## 4.3.2 Exploration Mode

The Exploration Mode of the experience allows the user to wander in the near-Earth space among satellites and debris. Movements in Virtual Reality (VR) is usually achieved by means of teleportation from the current position to a location a short way ahead [9]. This is done in order to limit the possibility of users getting motion sickness. The location to be reached has to lie on a plane intersecting a ray coming from the controller. However, having planes in space would feel very unnatural and would break the feeling immersion. Moreover, moving this way requires a bit of practicing and may not feel straightforward to people who are not used to VR. For these reasons, we decided to constrain movements to teleportation between navigation landmarks, marked by pink icosahedrons (Fig. 4.4). They are positioned in circles around the Earth at different heights, as can be seen in Fig. 4.5. Additionally, one is placed below the South pole and one above the North pole, to provide two inter-



A GEO satellite is always above the same place on Earth

*Figure 4.3: The user's point of view changes as the story progresses.*

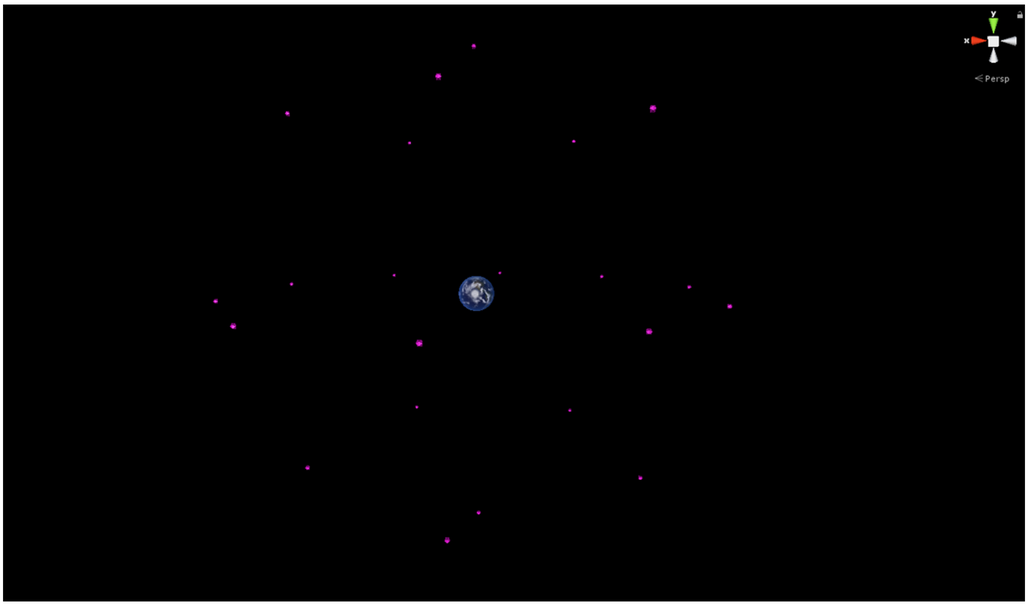


*Figure 4.5: Circles of navigation landmarks at different heights.*

esting points of view from which to look at the Earth and the surrounding space. The choice of the landmarks' color has fallen on pink to make it immediately clear that they are not real objects. When pointed to with the controller, icosahedrons start pulsating to show that they are activated. The user has to press the trigger button on the controller to teleport to the desired location. Another way to explore space is using the thumbstick. Moving it forwards or backwards allows the user to shift between navigation landmarks lying on concentric circles at different distances from the Earth.

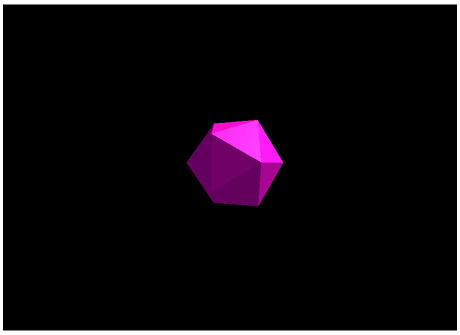


*Figure 4.4: Navigation landmark denoted by the pink icosahedron.*

While exploring, the user can decide to add or remove certain types of space objects from the view. This can be achieved opening the menu and toggling the activation of a particular kind of objects. The user can also highlight the satellites (in green the active ones and in red the defunct ones) or change the scale of all the objects. Three different scales are available. One of them provides a realistic sizing of satellites and debris with respect to the size of the Earth used in the experience. However, because such objects usually range from 30cm to 4-5m in size, they result very small compared to the planet that has a radius of 6,378km. To solve this problem, we decided to provide two additional scales which, although not scientifically accurate, make satellites and debris more visible, especially from afar.

*Figure 4.6: ASUS Windows Mixed Reality Headset and its controllers.*

## 4.4 Technologies

This section presents the headsets we used in the development of our application. Both of them are part of Microsoft's Mixed Reality project, an attempt to provide devices that span the entirety of the Reality-Virtuality Continuum (Fig. 3.15).

### 4.4.1 ASUS Windows Mixed Reality Headset

ASUS Windows Mixed Reality Headset (Fig. 4.6) is a Virtual Reality (VR) Head-Mounted Display (HMD). It is one of a series of VR HMDs produced by different vendors allowing users to have VR experiences on a Windows platform. It comes bundled with two controllers. It has two high-resolution liquid crystal displays (each 1440x1440) and provides an horizontal field of view of up to 105 degrees. For tracking purposes, the headset is equipped with two built-in front-facing cameras and 32 LED lights on each controller. Thanks to these and other embedded sensors (gyroscope, accelerometer, magnetometer), the environment can be mapped and the positions of the user and the controllers can be determined with 6 degrees of freedom without the need of additional external supports. However, users are not completely free to move in space since the headset is tethered to the PC. The headset weights less than 400g and has an headband designed to place most of its weight on the forehead and the back of the skull to lift the pressure from nose and face.

### 4.4.2 Hololens

Hololens (Fig. 4.7) are Microsoft's AR smartglasses. Released in 2016, they are self-contained and do not need to be tethered to a PC in order to function. No external cameras are employed for position tracking so the user is free to move in

Figure 4.7: Microsoft Hololens with their case, battery charger, and input device.

space. However, despite the advantage presented by the absence of wires, they have a limited processing unit on board, thus supporting only experiences that are not computationally intensive. Hololens feature an Optical See-Through (OST) display with an adjustable headband for a better weight distribution that saves the user's ears and nose from too much pressure. Interaction is mainly gaze-based with the addition of speech commands or gestures. An external input device with a button can be used in place of speech and gestures. Gesture recognition is performed by cameras placed on top of the display that also perform tracking and spatial mapping.

## 4.5 Application's Architecture

As shown in Fig. 4.8, the application relies on a client-server architecture. Each part is in charge of specific functions. The remote server handles the computations required by the simulation of the ∼20000 space objects' movement. In particular, it has to calculate their position every frame and send it to the client. The decision of having the whole computational load running on the server was given by the fact that we want our application to be easily affordable and this separation allows us to run the client part on less costly headsets with limited processing power. Accordingly, the client application is responsible only of visualising the space objects and receiving inputs from users. It can run both on tethered or untethered headsets, which are usually less performant, since the heavy computational load rests on the server.

### 4.5.1 Technological Challenges

**Entity Component System**

One of the major challenges we had to face was to manage around 20000 objects in the scene at the same time and update all their positions every frame. This had to be done without affecting the smoothness of the experience since low refresh rates in VR are one of the primary causes of simulator sickness in users. The traditional

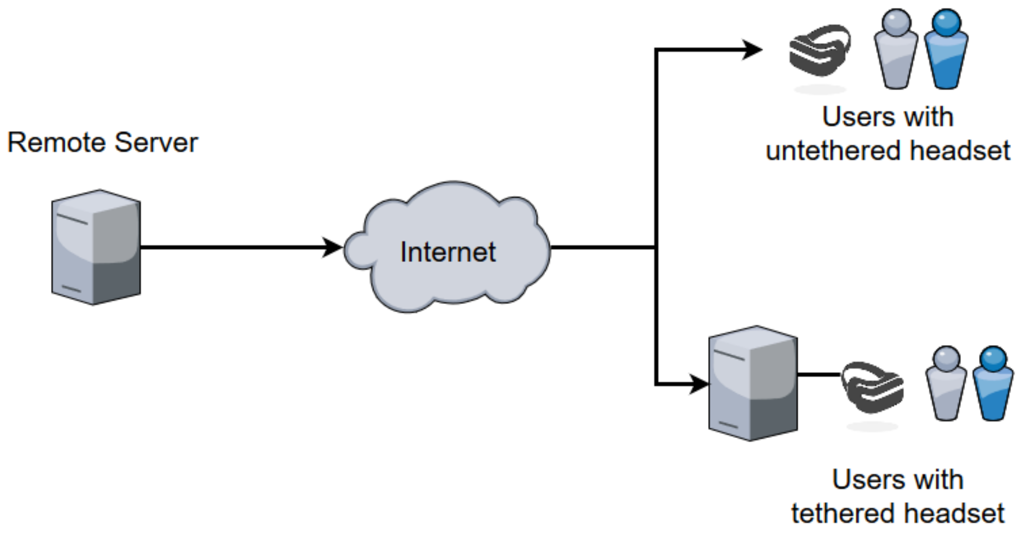


*Figure 4.8: The application's architecture*

object-oriented approach, however, proved to be insufficient as it led to very poor performances (15-20 frames per second). For this reason, we decided to follow an Entity Component System (ECS) pattern for our code. ECS enforces a data-driven approach to programming given by a clear distinction between data and logic. It relies on three fundamental concepts: entities, components, and systems. Entities are just IDs used to index a collection of different components. Such components wrap only data and they do not contain any logic to manage it. Systems are where all the logic is placed. They filter entities based on the components they need to carry out their task so that they can processes only the suitable entities. Fig. 4.9 shows an example of ECS. Entities (Bullet, Player, and Enemy) contain a list of components (Render, Position, Health, etc..). Each system is associated with a filter specifying the components it needs. For example, the Render System only needs the Render and Position components so all the three entities will be processed by it. Systems are unaware of which components entities have out of those they need for their functioning.

### Remote Server and 5G

Every frame, the remote server sends all the objects' positions to the client. In doing so, a connection with minimum latency is required to avoid affecting the smoothness of the experience on the client's side. For this reason, our application is part of a collaboration with Vodafone Italia aimed at showing the benefits of 5G. Thanks to its efficiency, it is possible to send data with a very low latency. Furthermore, as future development, we are planning to:

- move also the visualisation to the remote server so that the client application will receive directly the images to show on the displays and will send all the inputs (head tracking, state of the controllers' buttons etc..) to the remote

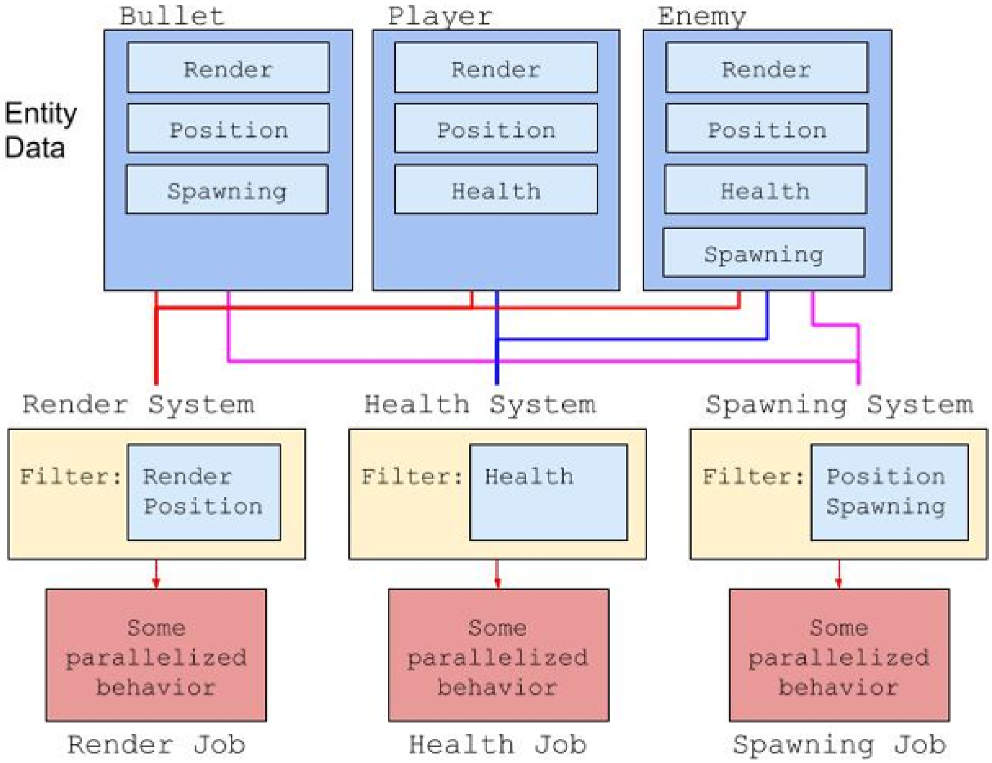


*Figure 4.9: An example showing how ECS works (from [8]).*

server to properly synchronise the received images with the actual state of the user.

- add the "multiplayer" feature for classes so that the application will allow more people connected at once.

These two improvements, in addition to the low latency, require a high bandwidth to support the simultaneous connections which is currently unavailable but will be provided by 5G.

### Support for Different Input Devices

One of the main requirements of the experience was to support the very different interaction patterns and input devices of both AR and VR. Moreover, new commercial headsets are being released at an unprecedented pace [4] and we wanted to be able to eventually port our experience to novel platforms with minimum effort. These have been the major driving forces that led the design of our software. Fig. 4.10 shows an high-level view of our application's software architecture. The *Core* is responsible of managing the objects' movement and is placed in the remote server. The calculated positions are sent to the client application by the *NetworkSender*. On the client's side, the *NetworkReceiver* gets the coordinates and passes them to the *Visualisation* module which, as the name implies, is responsible for the final rendering of the scene. The *CommandManager* provides a layer of abstraction that exposes all the functionalities available to users. This way, changing platform only requires modifying the Platform-Dependent Input module which calls the CommandManager's features.

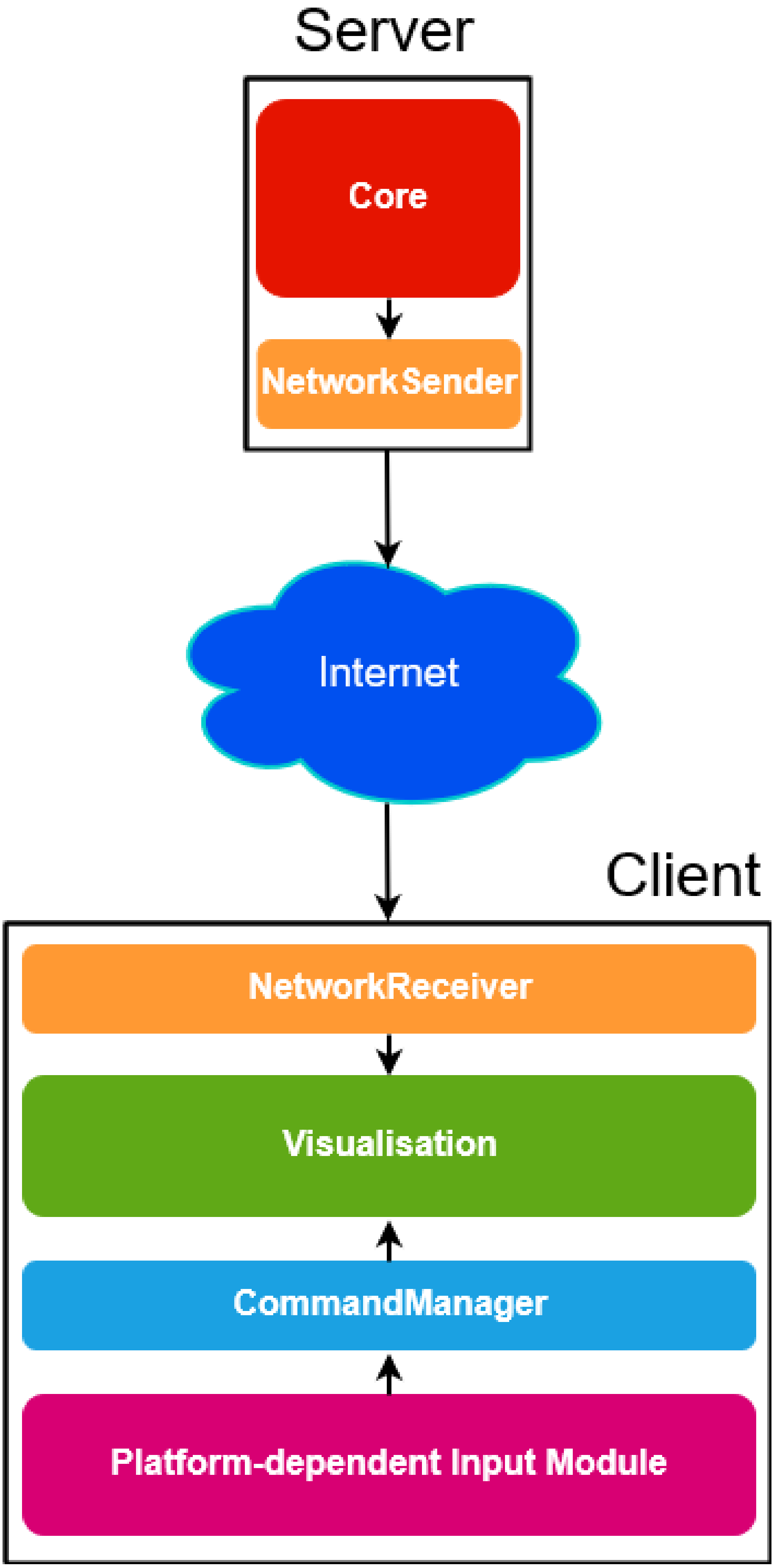


*Figure 4.10: The application's software architecture.*

# Chapter 5

# The Space Debris Application

This chapter details the flow of the application and provides illustrations of all the settings in which users find themselves during the experience. All the scenes that have been part of the application are included, even if they do not appear in the latest prototype. All the images are taken from the Virtual Reality (VR) version of the experience because of the intrinsic technological difficulties of providing Augmented Reality screenshots.

## 5.1 The Structure of the Experience

The experience is composed by two different modes: the Story Mode and the Exploration Mode. The former was divided in two scenes until MeetMeTonight 2018 (28-29 September). After that, in face of the issues arisen during the event, it was restructured and compacted in a single scene. The Exploration Mode is set in space and allows users to wander among satellites and debris. In this mode, it is also possible to activate, deactivate or highlight certain types of space objects from the menu, change their scale, and see the trajectories of the satellites.

## 5.2 Story Mode

The Story Mode introduces users to the space debris problem. The first version was composed by two scenes, the first one set in the control room of a space station and the second providing a general view on the Solar System. Because of the issues of this layout pointed out by the visitors of MeetMeTonight 2018 (28-29 September), we restructured it in a single scene and extended the story adding more information on satellites to make it more interesting.

### 5.2.1 First Version

At the beginning of the story the user finds herself in the control room of a space station with blank terminals around her, as shown in Fig. 5.1. The screens switch on one at a time from left to right (Fig. 5.2) displaying information on space debris.

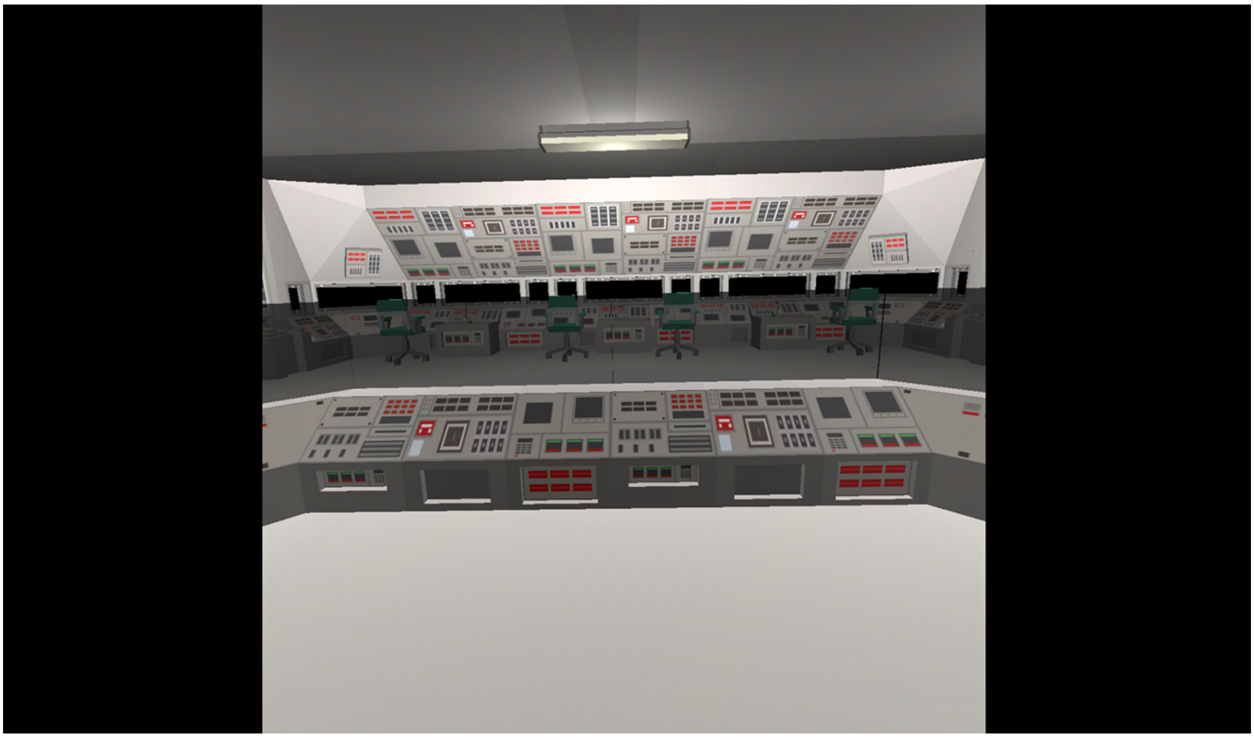


Figure 5.1: The beginning of the story in the control room of the space station.

When all the terminals are on, the launch door appears behind the user (Fig. 5.3).

After clicking on the launch button, the user finds herself in the Solar System (Fig 5.4). Several planets, although small, can be seen around the Sun. The Earth presents a clue on how to proceed with the experience. Right after entering the scene, Jupiter and Saturn can be found behind the user (Fig. 5.5). After clicking on the Earth, users are brought to the tutorial.

### 5.2.2 In Space

After being restructured, the Story Mode was set in near-Earth space. At the beginning, the user finds herself a short distance from the Earth, facing it, with an informative screen right ahead, as shown in Fig. 5.6. No objects a part from the Internation Space Station (ISS) are visible at this point. Progressing with the narration, more objects start to appear (Fig. 5.7). This version of the Story Mode was expanded including information on the satellites orbiting around the Earth (Fig. 5.8 and Fig. 5.10) to make it more captivating. In order to view also those that travel at higher distances, the user is teleported farther from the Earth, as shown in Fig. 5.9.

## 5.3 Exploration Mode

The Exploration Mode allows users to wander in space among satellites and debris. Objects can be viewed with different scales depending on the user's taste (Fig. 5.11,

is always above
ace on Earth.

There are currently 20000 pieces
of debris tracked.

*Figure 5.2: The terminal start switching on from left to right presenting information on space debris.*

5.12, 5.13). It is also possible to highlight the active satellites in green and the defunct ones in red, as shown in Fig. 5.14.

### 5.3.1 Navigation Landmarks

To move in space, navigation landmarks, denoted by pink icosahedrons (Fig. 5.15), have been placed all around the Earth (Fig. 5.16). Fig. 5.17 and Fig. 5.18 show the Earth viewed respectively from the landmark above the North Pole and the one below the South Pole.

### 5.3.2 The Exploration Menu

The menu (Fig. 5.19) allows to choose which types of objects to view. Figures from 5.20 to 5.26 show space with only one kind of object active at a time.

### 5.3.3 Trajectories

While exploring the Earth the trajectories of particular types of satellites can be visualised. Fig. 5.27, 5.28, 5.29, and 5.30 show respectively the trajectories of the Low Earth Orbit (LEO), Medium Earth Orbit (MEO), GPS, and Geostationary (GEO) satellites.

*Figure 5.3: The launch door displaying a clue on how to use it to proceed in the experience.*

## 5.4 Tutorial

The tutorial was devised as a mean to teach users how to access with the controller the multiple functionalities offered by the experience. Initially, it was placed after the Solar System scene. However, after the restructuring of the scenes that followed MeetMeTonight 2018, it was embedded at the end of the Story Mode set in space. The images provided in this section refer to the last version of the tutorial. However, the only difference between the two versions is the background. No change was made to its flow.

Firstly, users are presented with a navigation landmark (Fig. 5.31). A text clue informs them that those spots serve to teleport between different positions in space. To proceed with the tutorial users need to click on the navigation landmark. Then, users are taught how to use the thumbstick to move closer or farther from the Earth (Fig. 5.32 and 5.33). Finally, the tutorial shows which button to use to open the menu (Fig. 5.34). Once opened (Fig. 5.35), text clues explain how to use it to activate and deactivate objects and what to do to close it and start exploring space.

*Figure 5.4: The view of the user after entering the Solar System. The Earth presents a clue on how to proceed with the experience.*

*Figure 5.5: Jupiter and Saturn*

*Figure 5.6: The beginning of the story in space. The user faces the Earth and only the ISS is visible.*

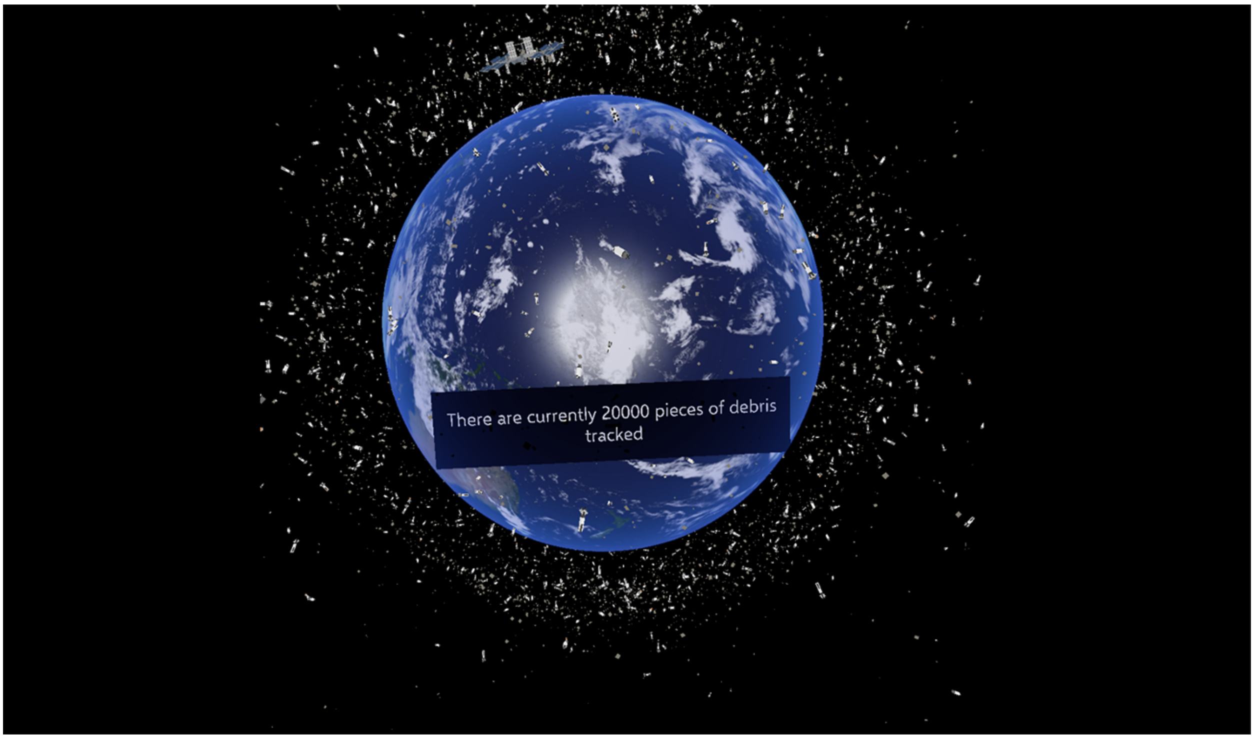
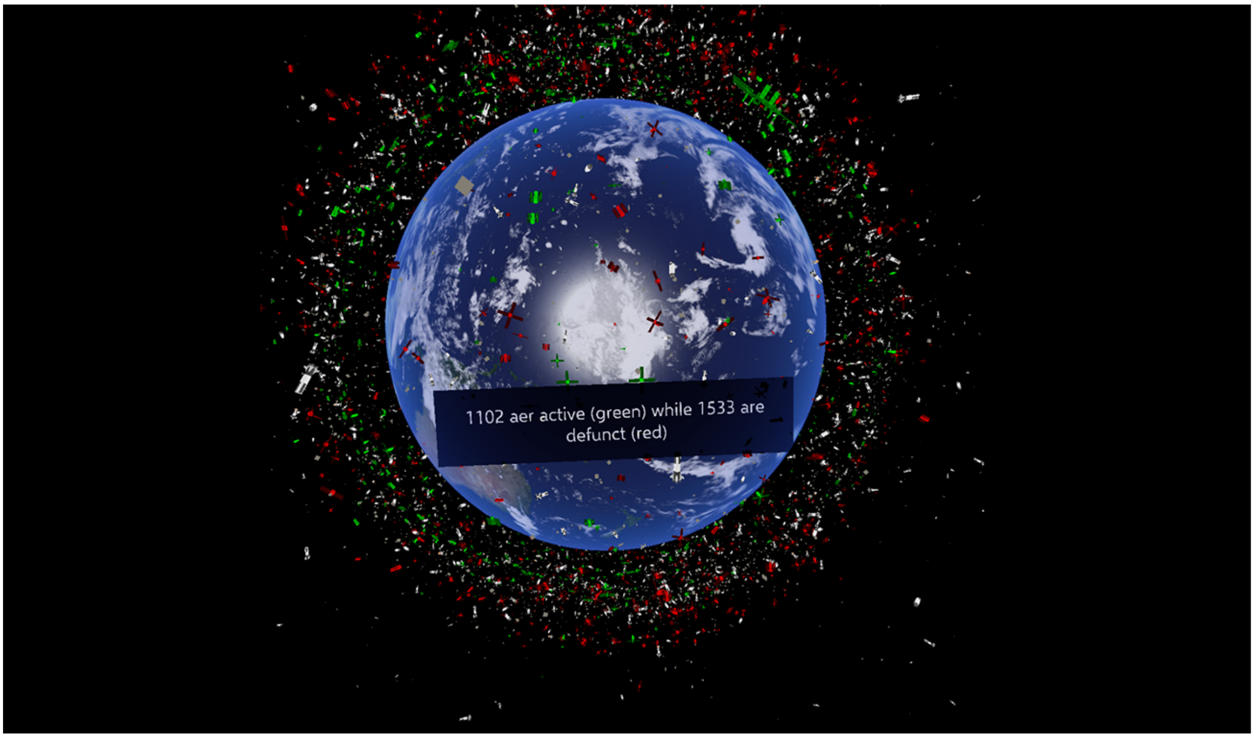
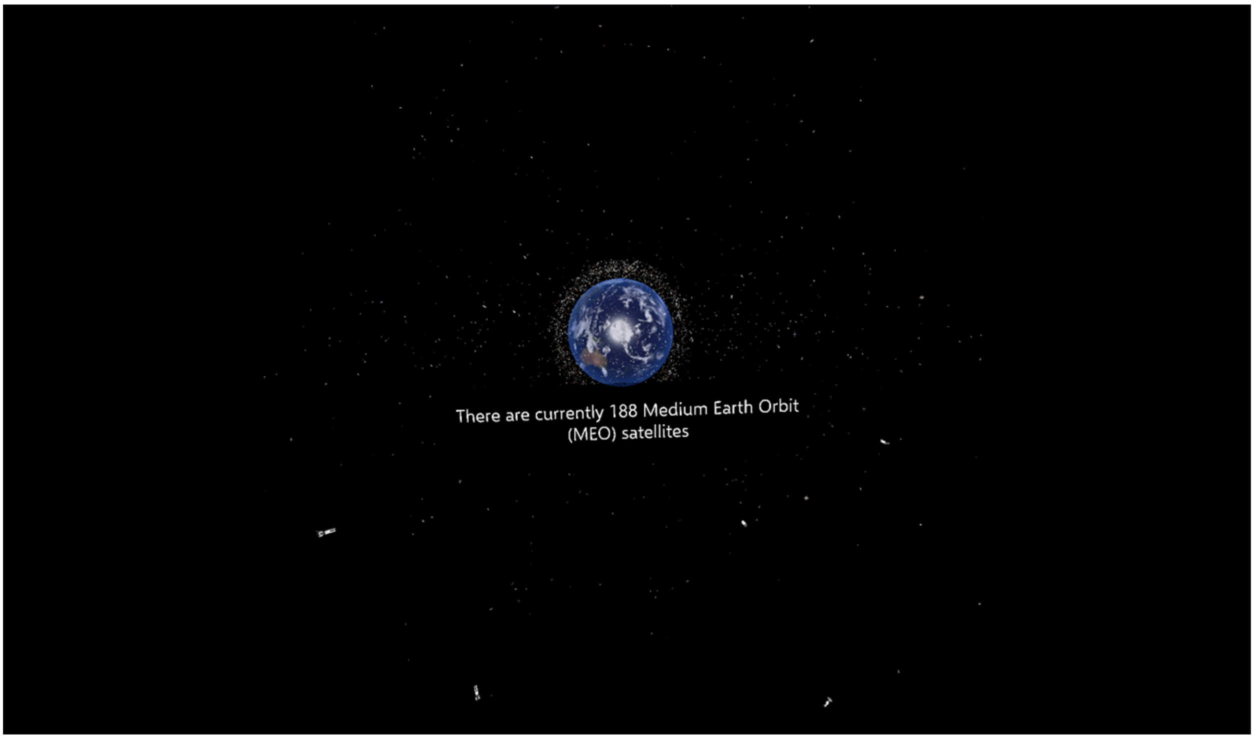


*Figure 5.7: As the narration progresses, more objects appear.*



1102 aer active (green) while 1533 are defunct (red)

*Figure 5.8: The Story Mode has been expanded to include also information on the satellites.*



There are currently 188 Medium Earth Orbit (MEO) satellites

*Figure 5.9: As the story progresses, the user is moved farther from the Earth to view also satellites that orbit at higher distances.*

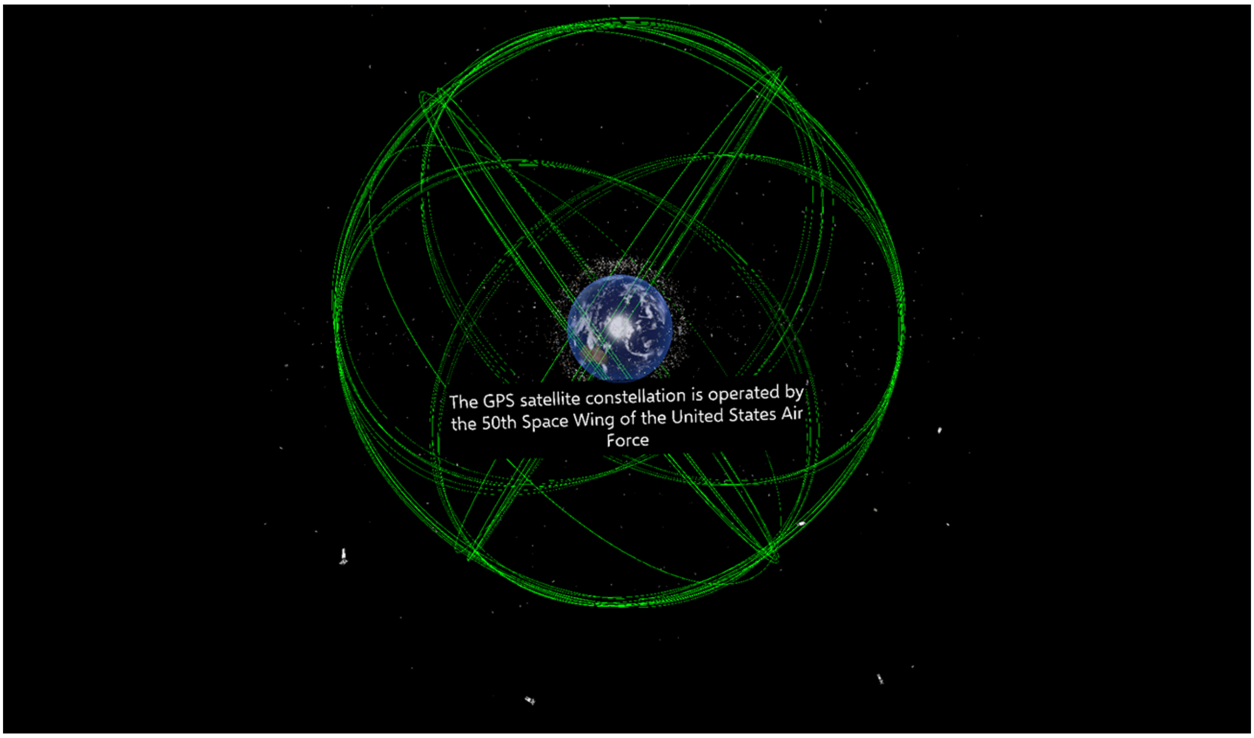


*Figure 5.10: An extract on the information about the GPS satellites. The green lines represent the orbits of the 31 satellites that compose the NAVSTAR GPS constellation.*

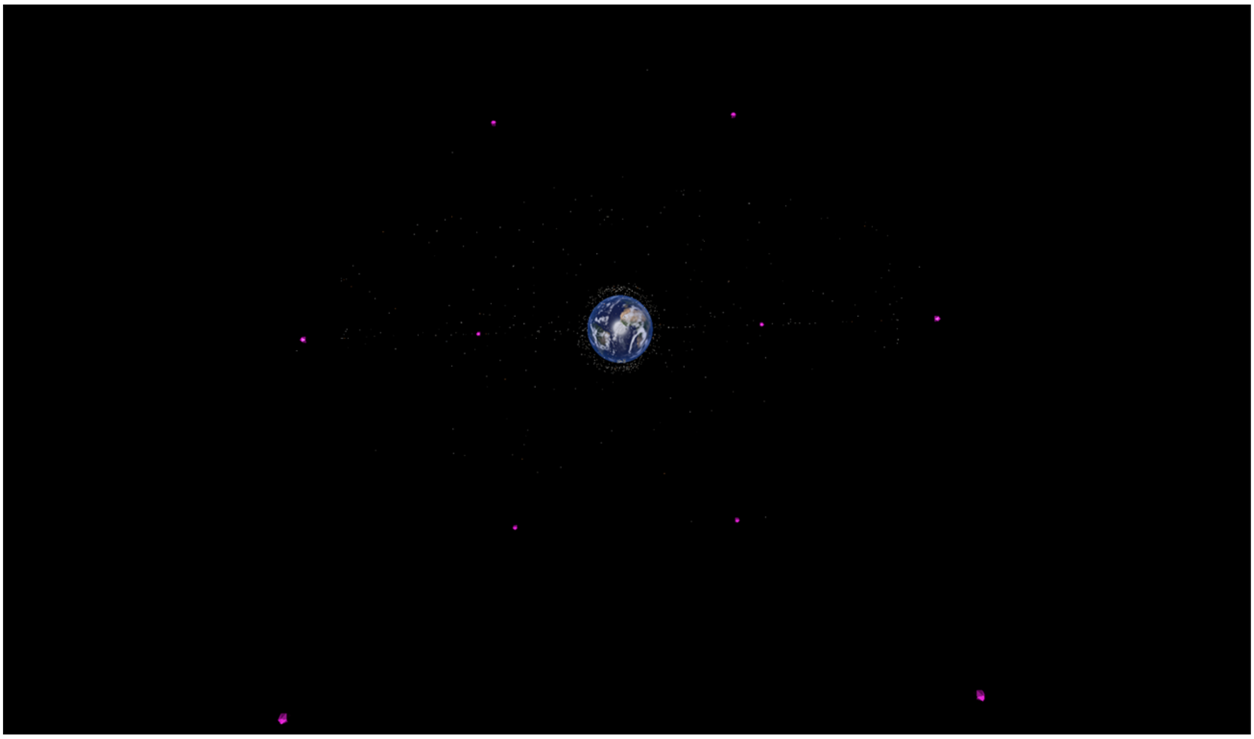


*Figure 5.11: The smallest and more scientifically accurate scale of the objects.*

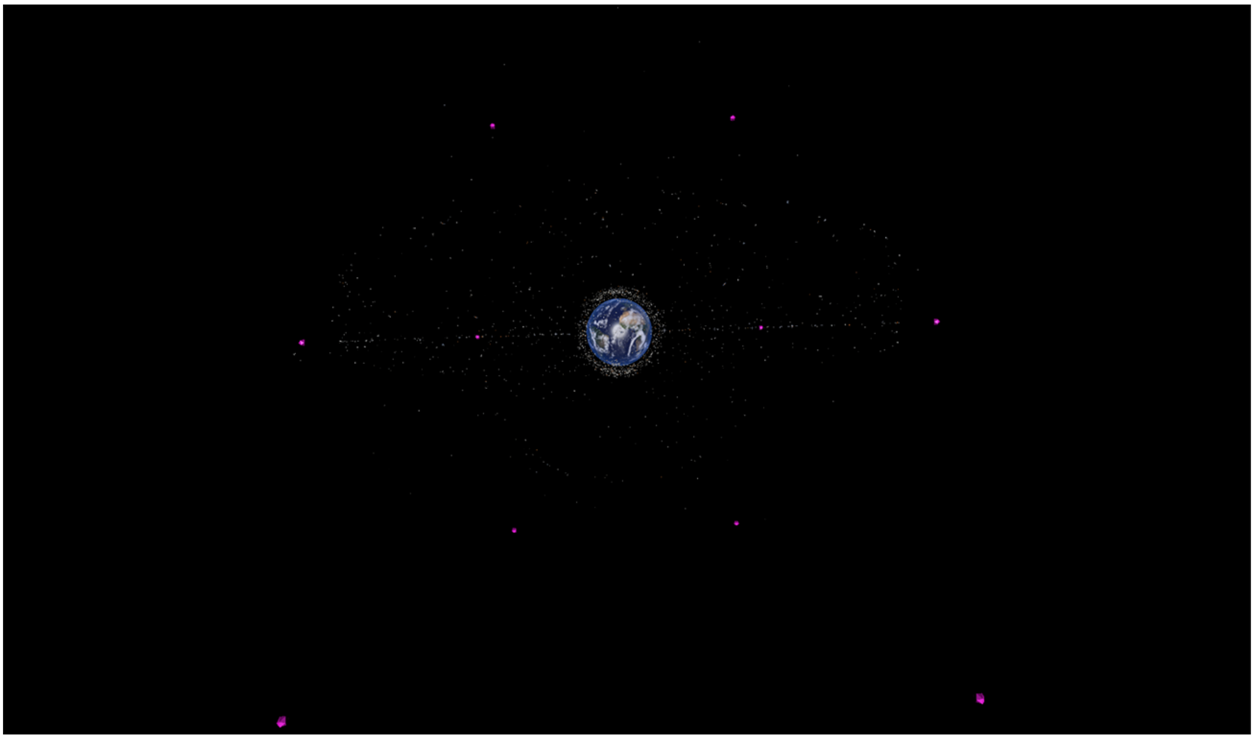


*Figure 5.12: The medium scale of the objects.*

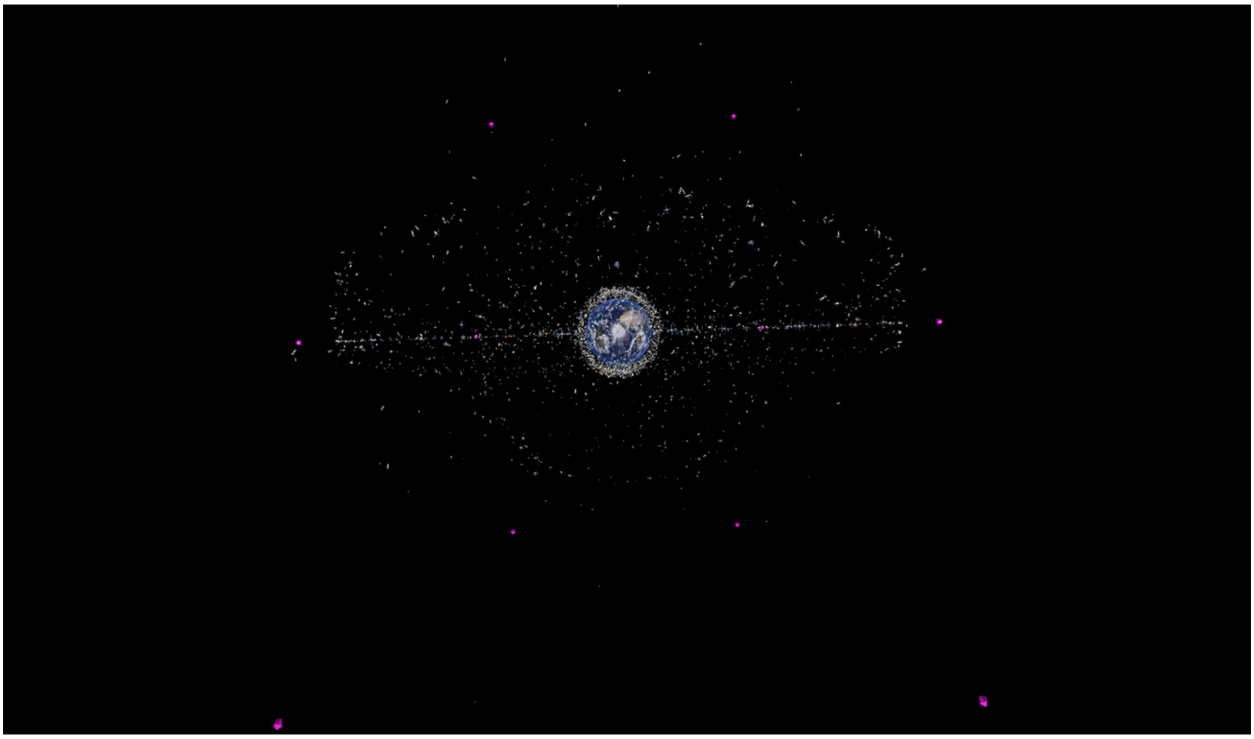


*Figure 5.13: The biggest scale of the objects.*

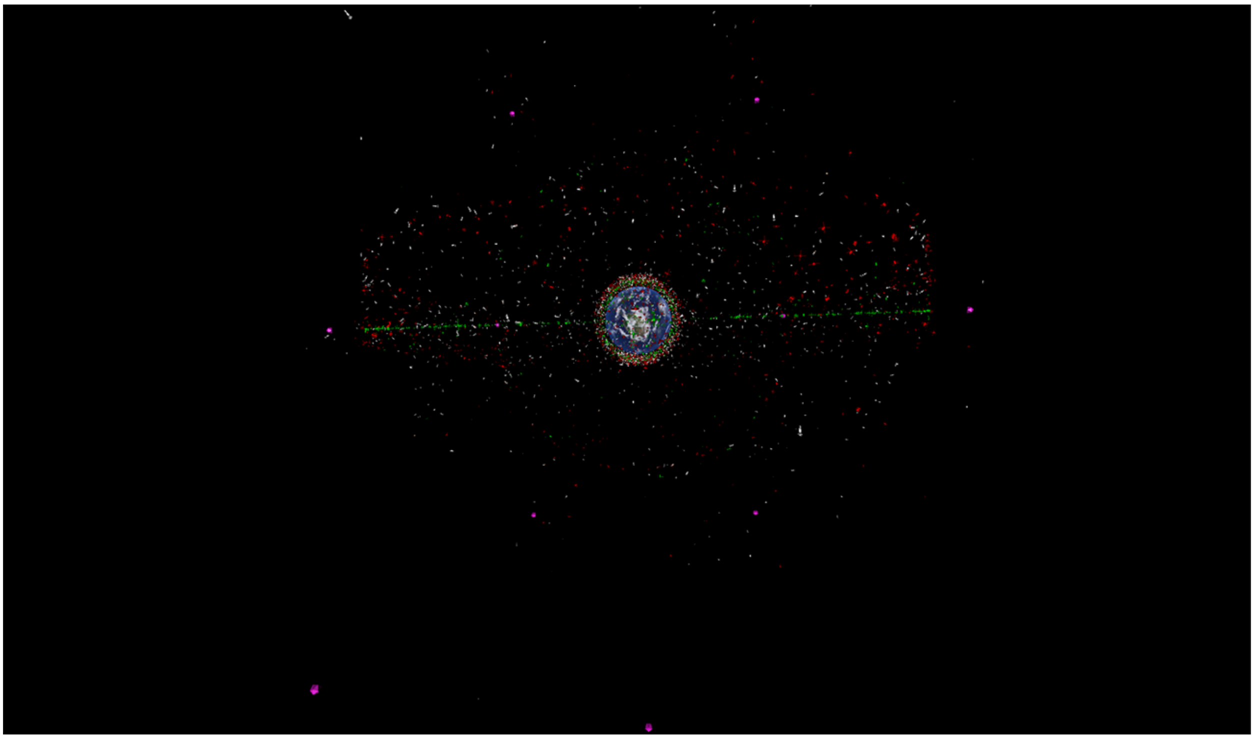


*Figure 5.14: Active satellites are in green, red satellites in red.*

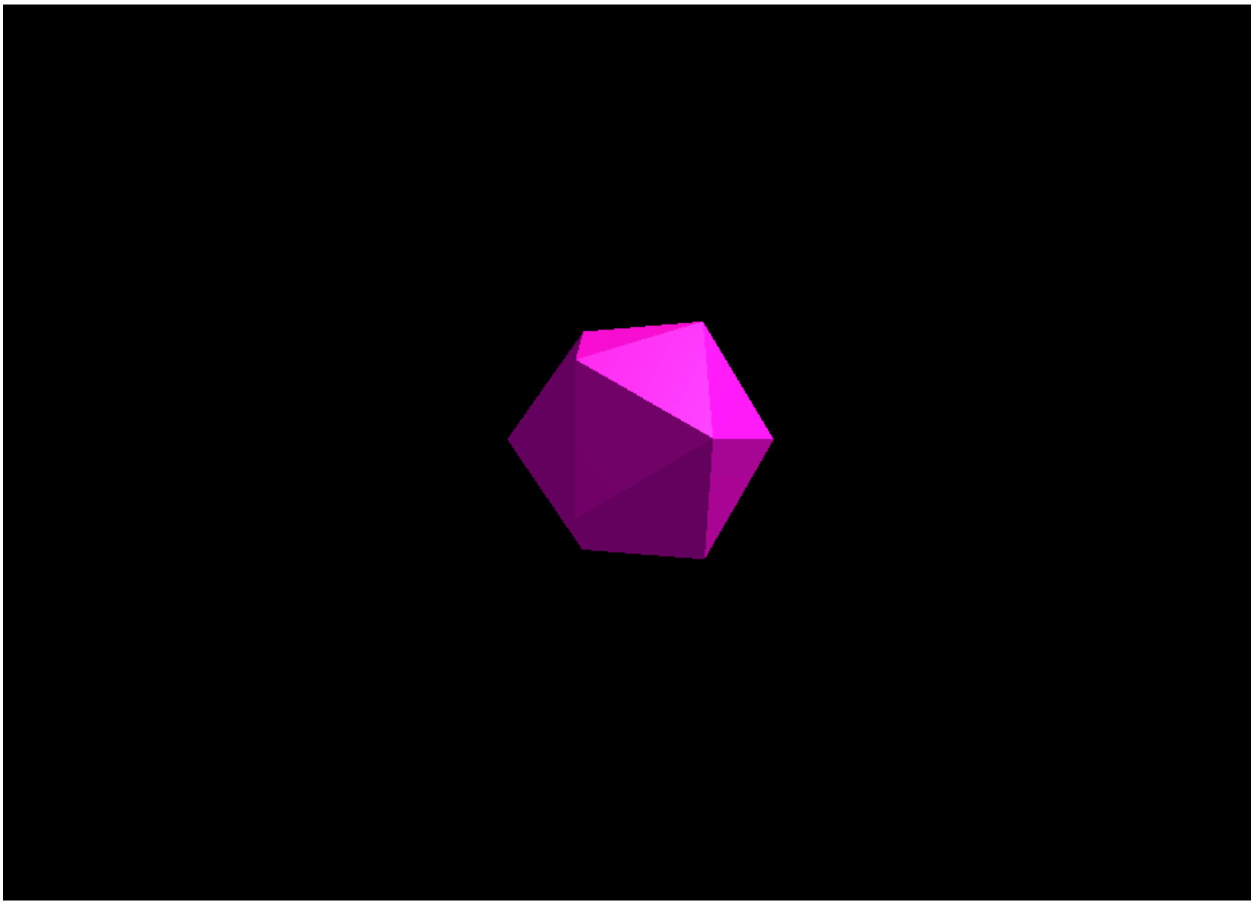


*Figure 5.15: The pink icosahedron denoting a navigation landmark.*

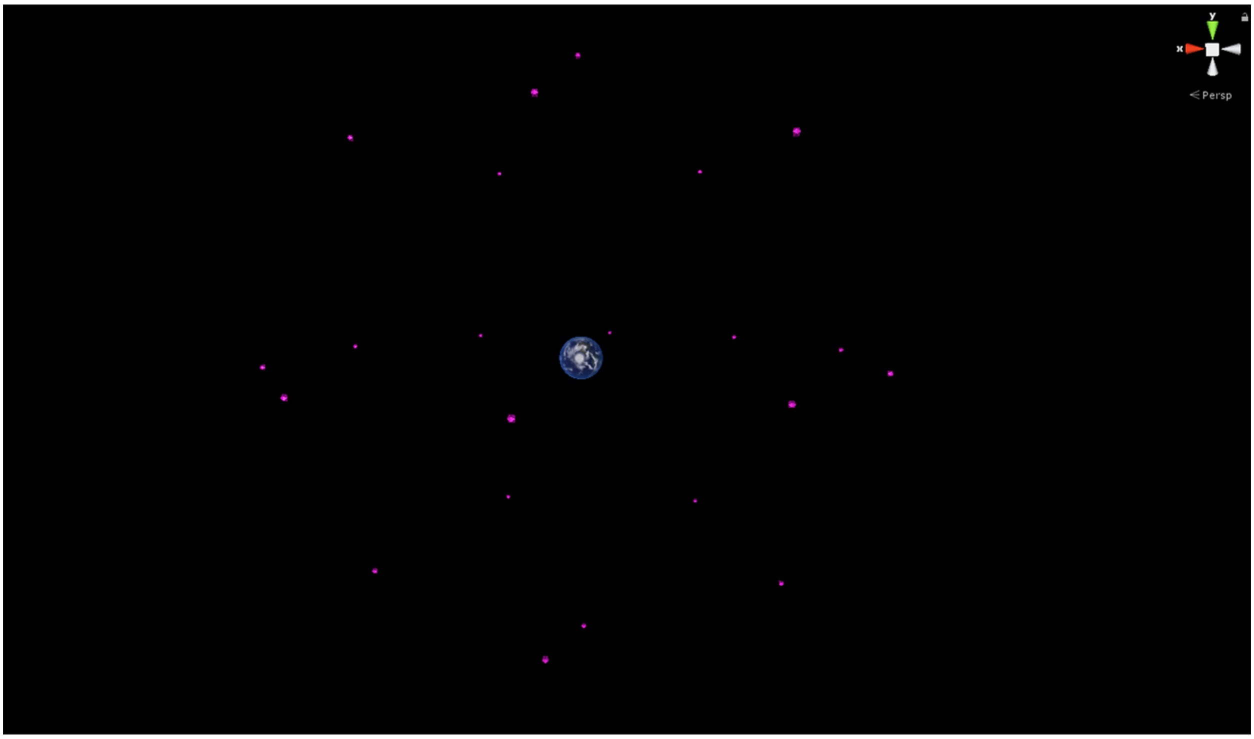


*Figure 5.16: Circles of navigation landmarks placed around the Earth at different heights.*

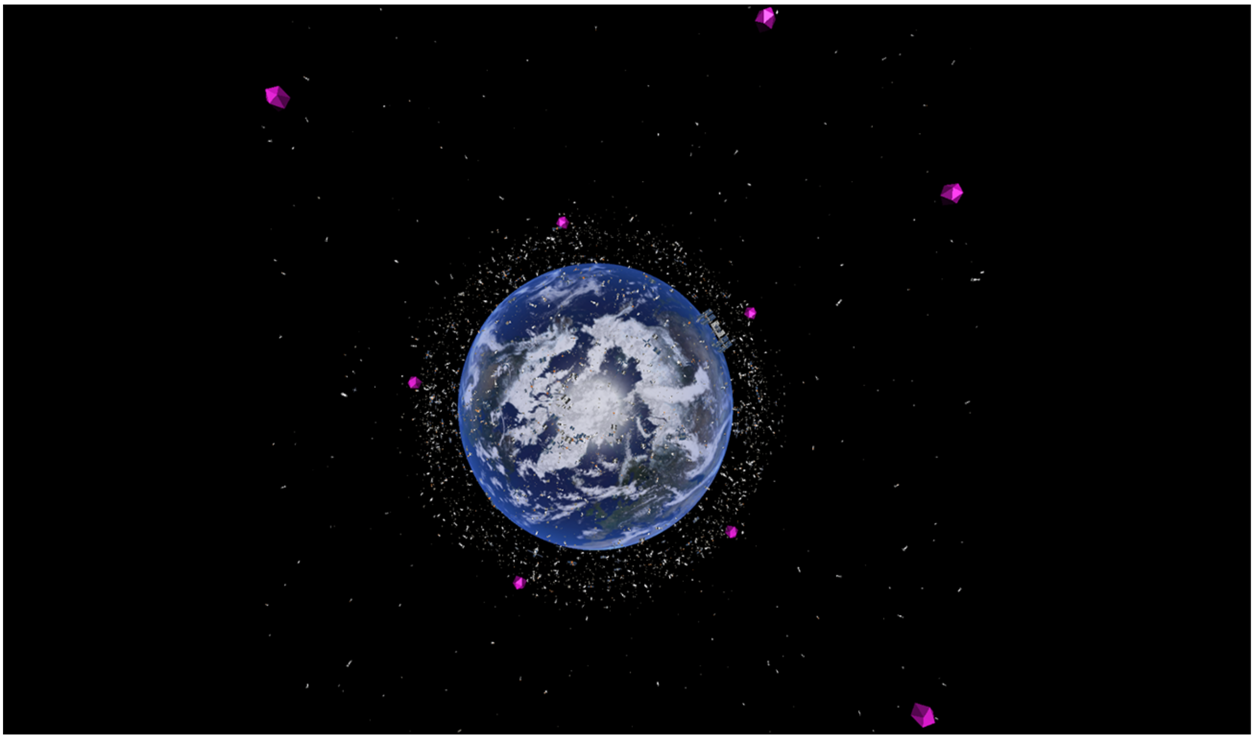


*Figure 5.17: The Earth viewed from the navigation landmark above the North Pole.*

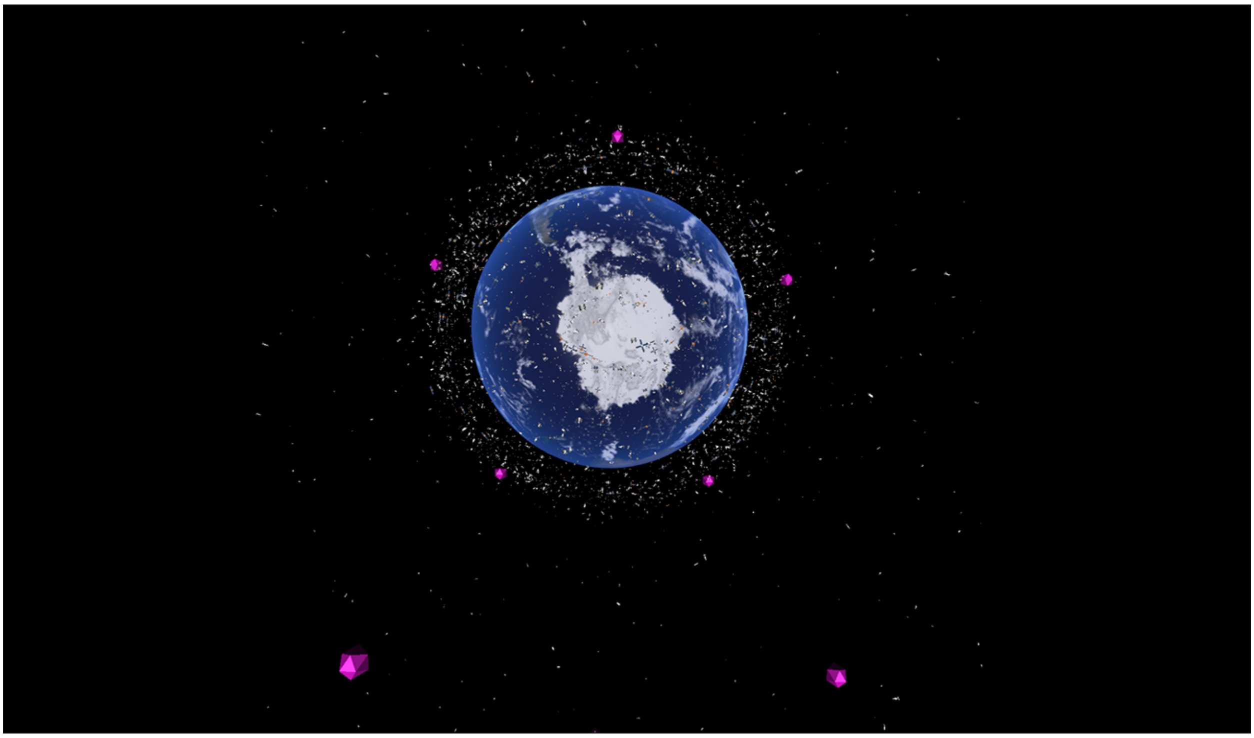


*Figure 5.18: The Earth viewed from the navigation landmark below the South Pole.*

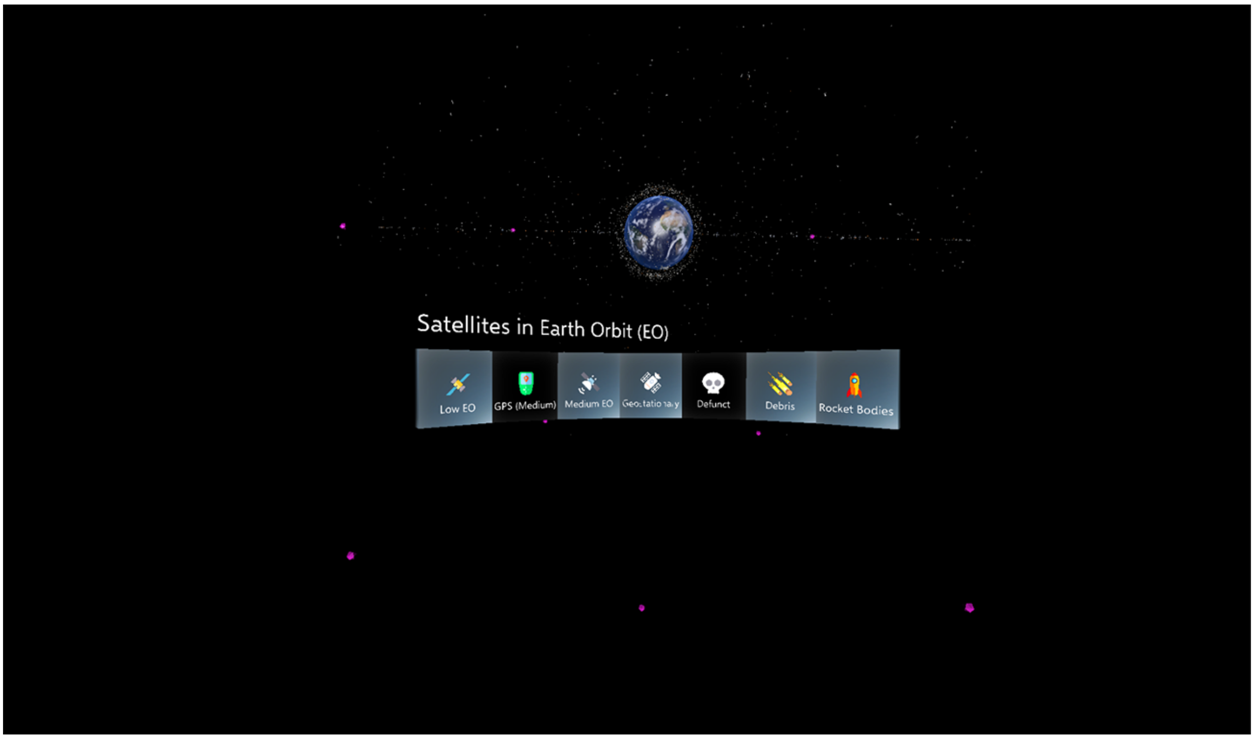


*Figure 5.19: The menu from which users can activate or deactivate objects. When a particular type of objects is deactivated, its button appears darker.*

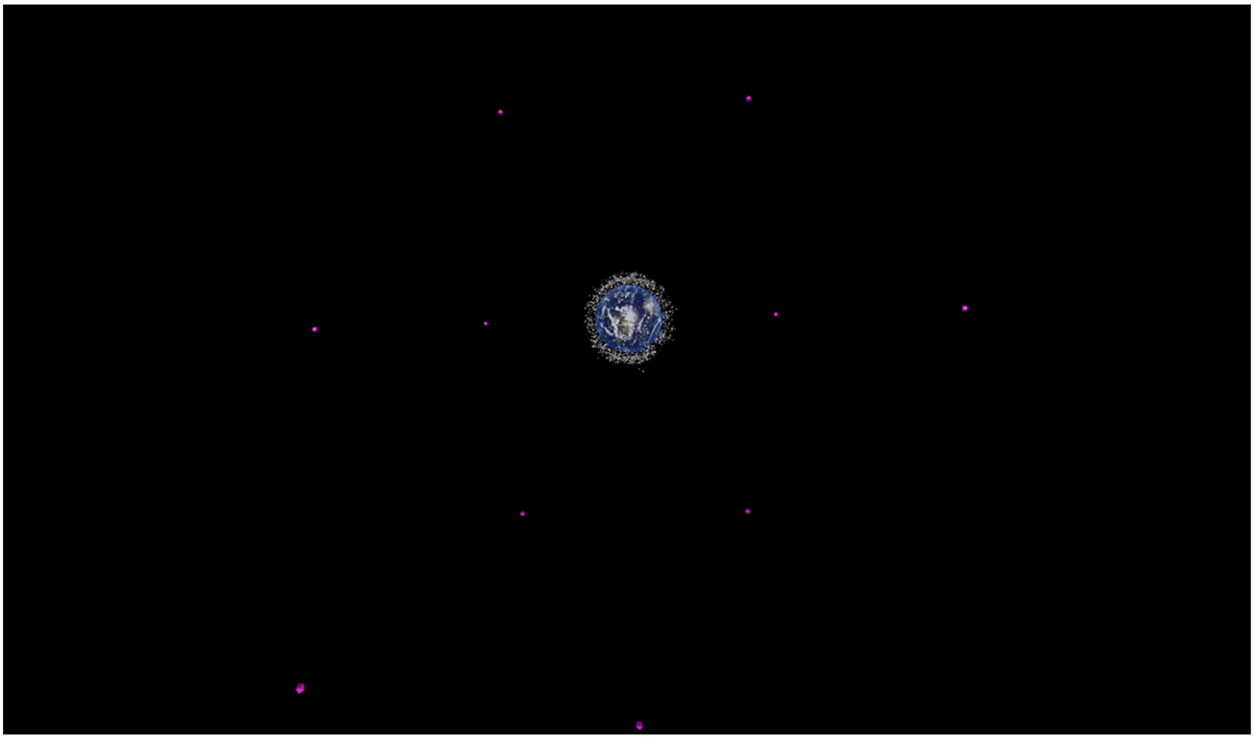


*Figure 5.20: Space with only Low Earth Orbit satellites.*

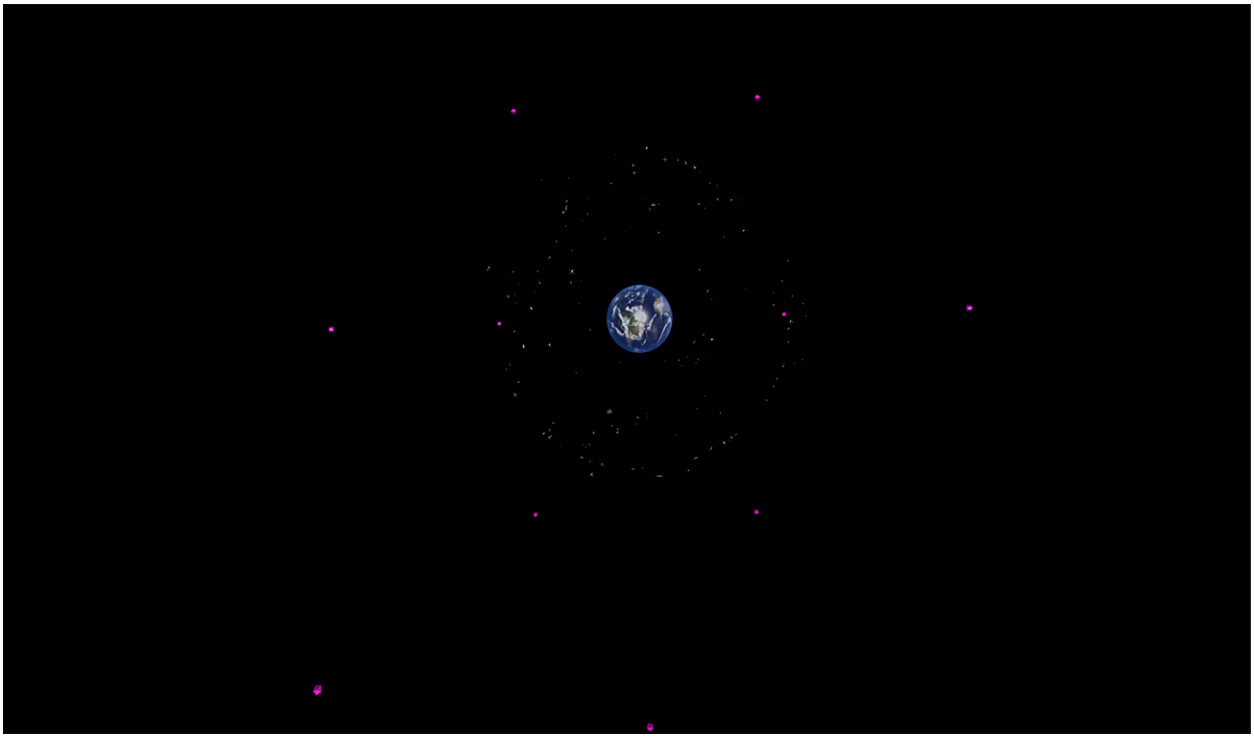


*Figure 5.21: Space with only Medium Earth Orbit satellites.*

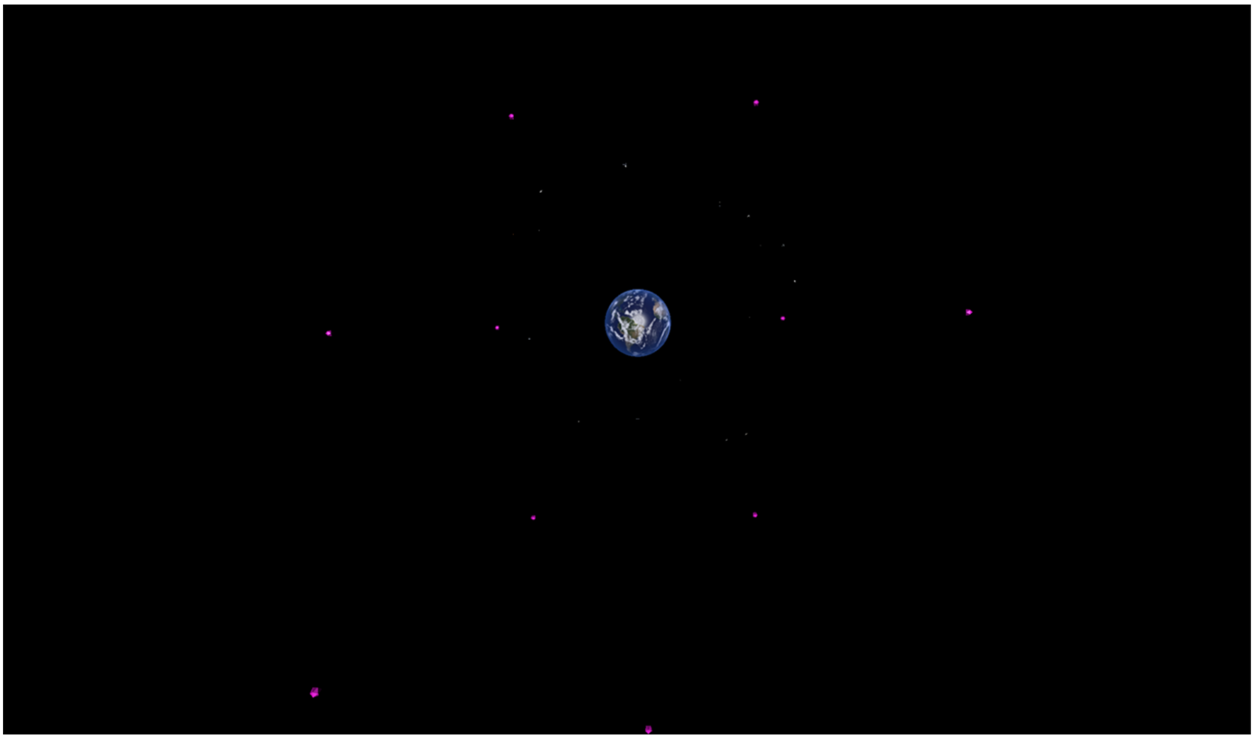


Figure 5.22: *Space with only GPS satellites. Being only 31, it is difficult to see them.*

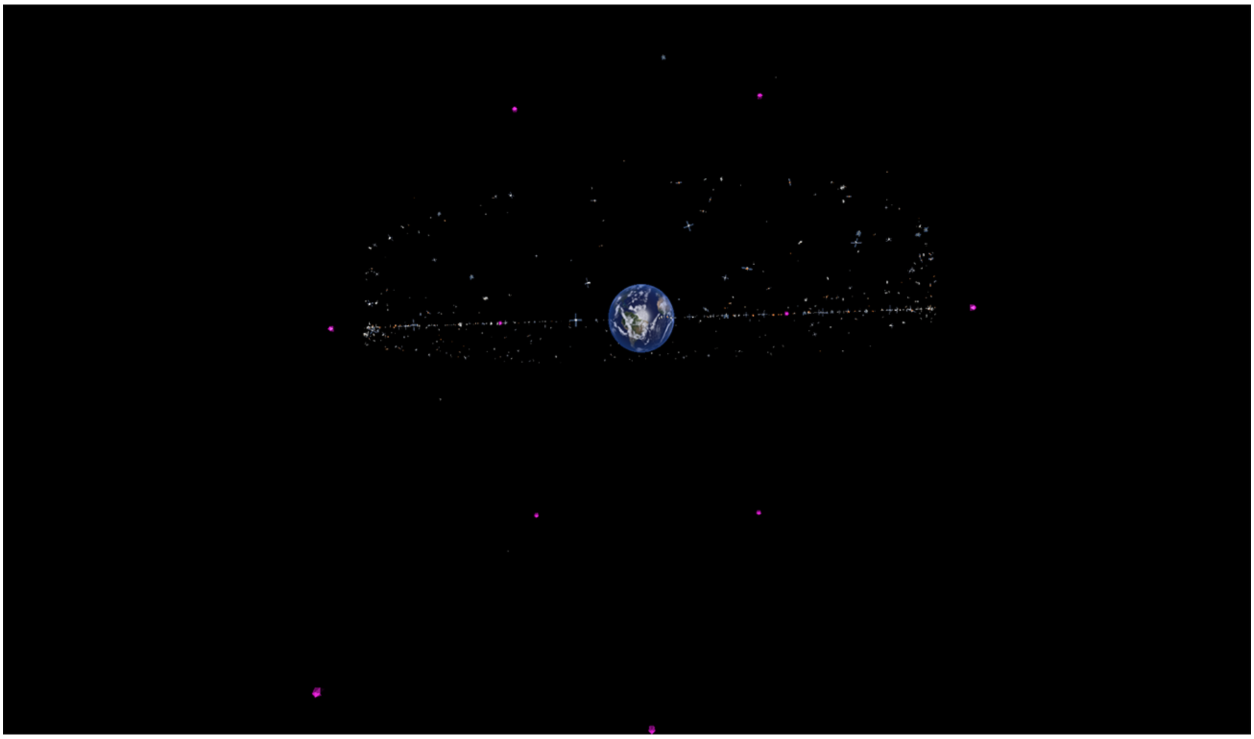


Figure 5.23: *Space with only Geostationary satellites.*

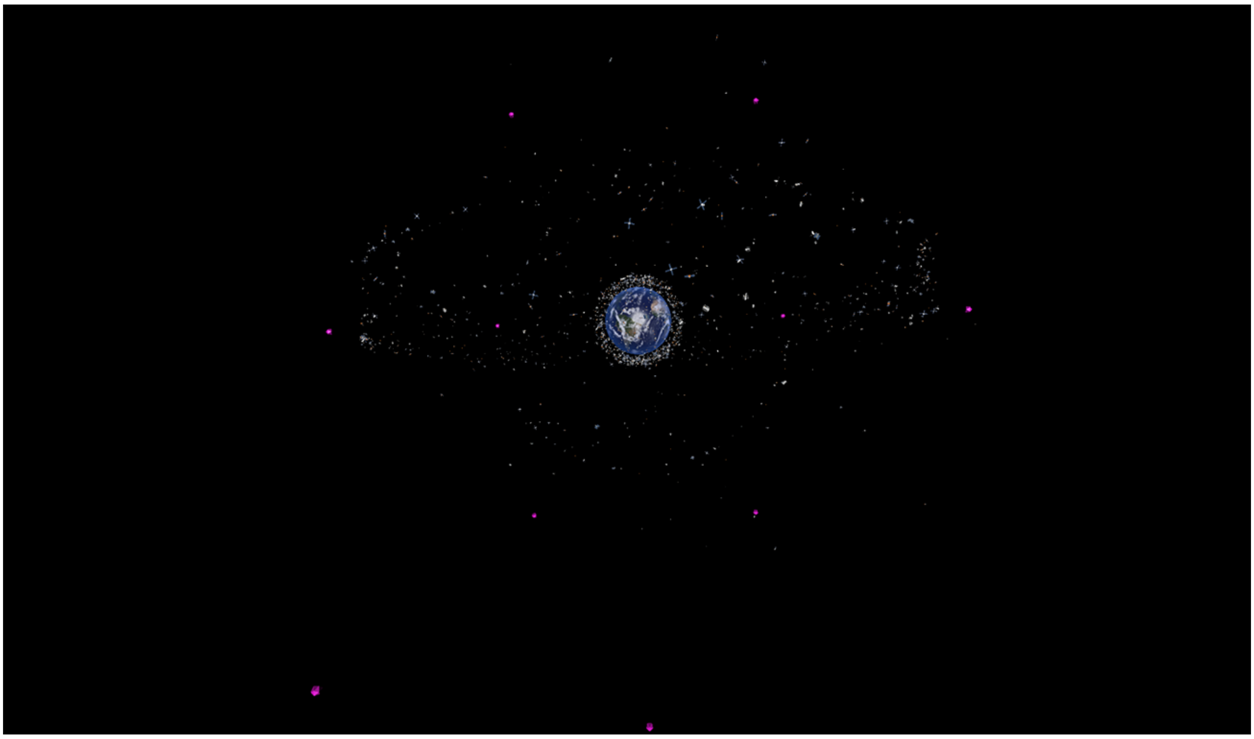


*Figure 5.24: Space with only defunct satellites.*

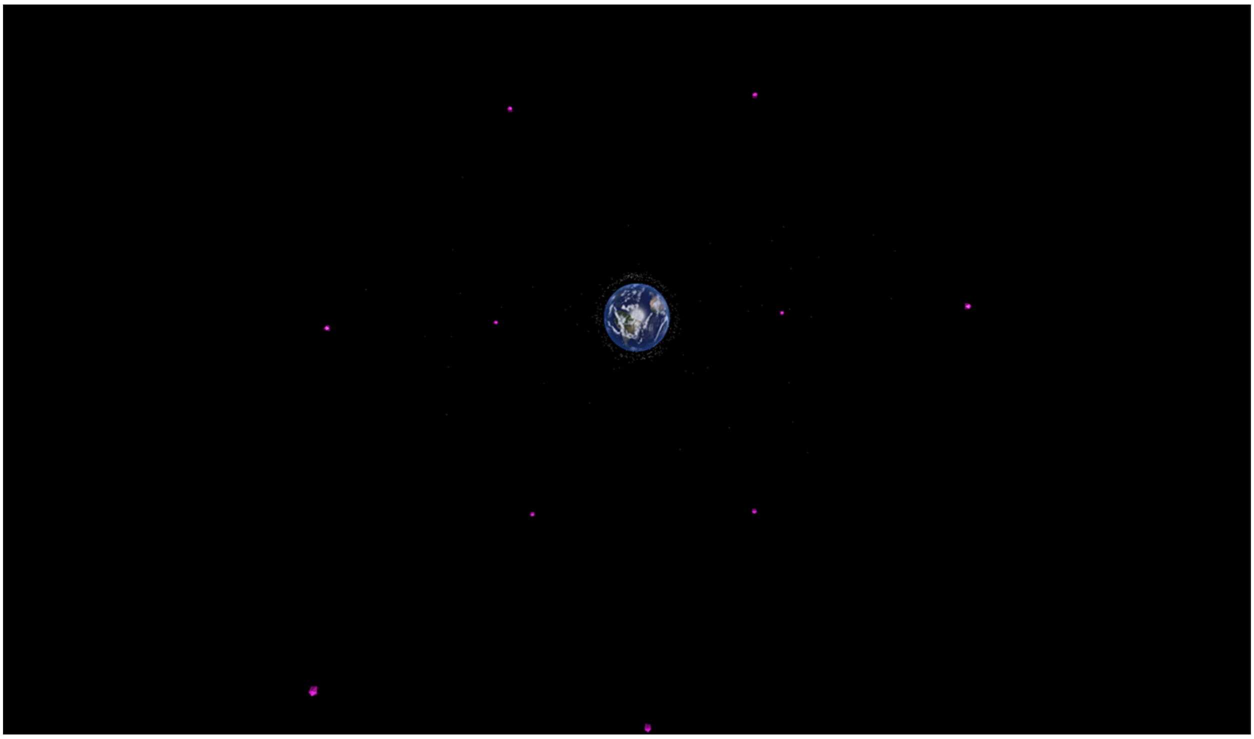


*Figure 5.25: Space with only fragmentation and explosion debris.*

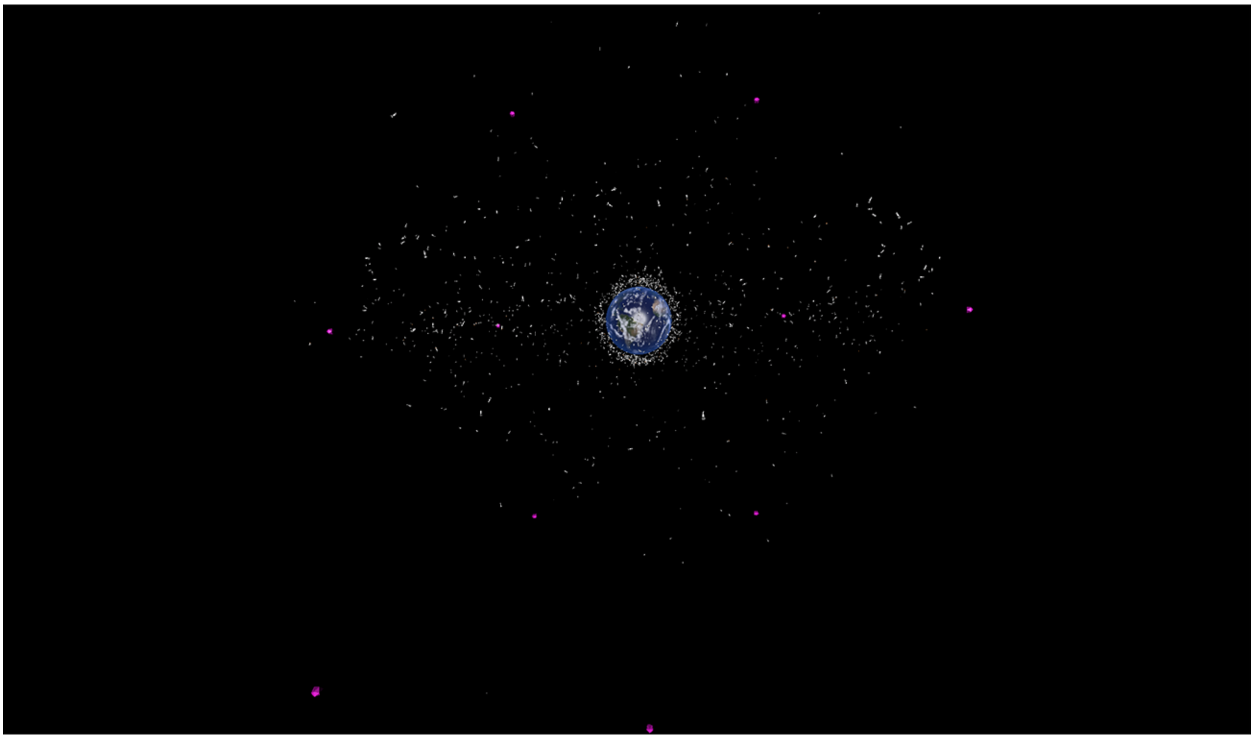


Figure 5.26: Space with only rocket bodies.

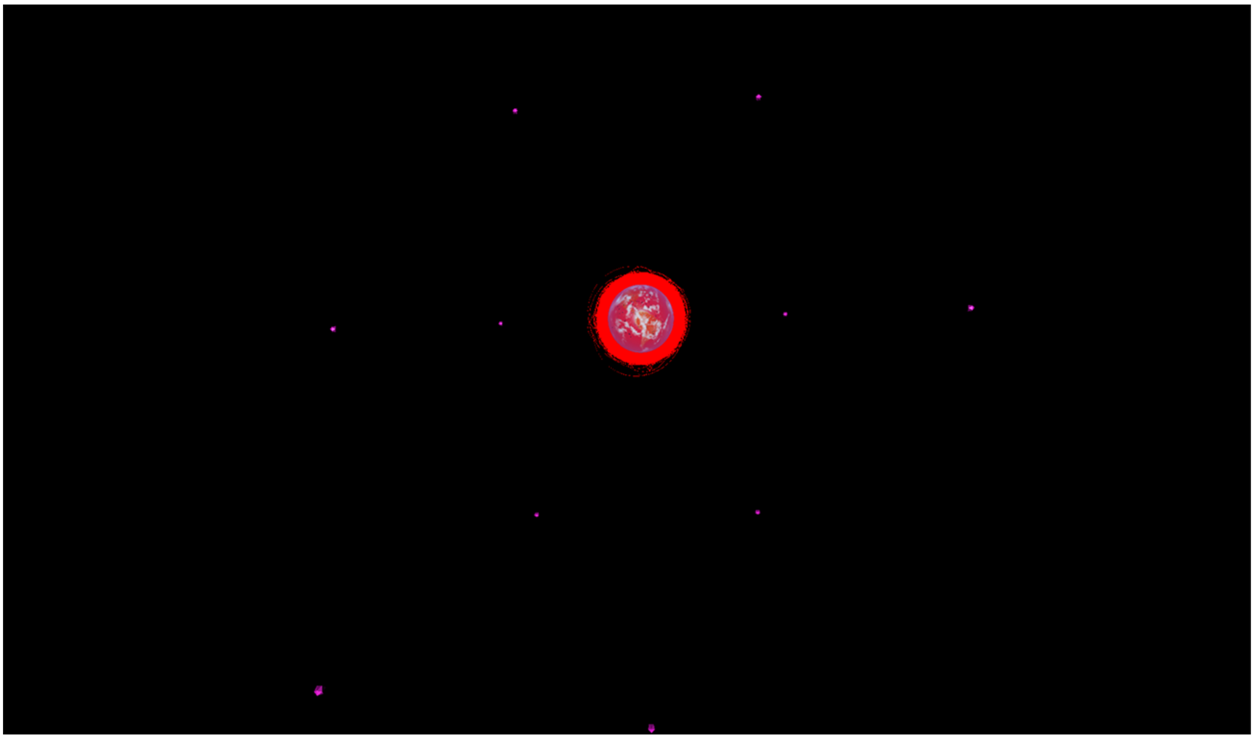


Figure 5.27: The trajectories of the LEO satellites.

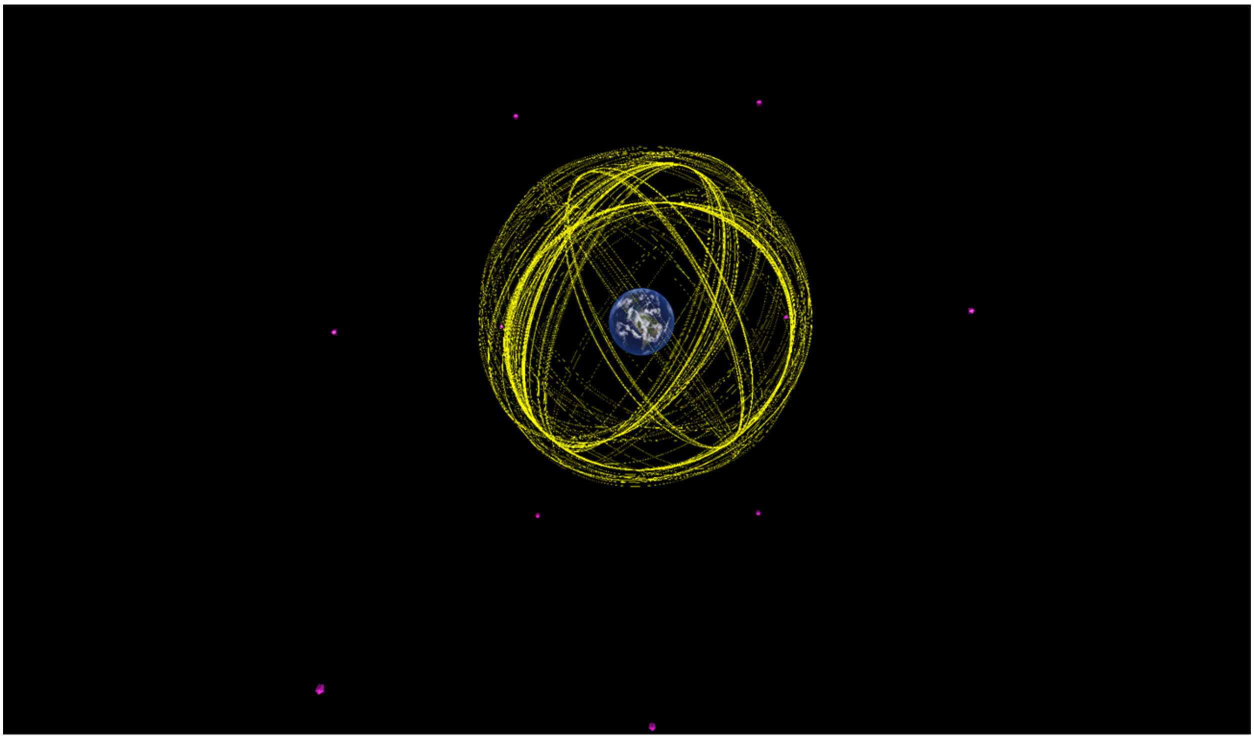


Figure 5.28: The trajectories of the MEO satellites.

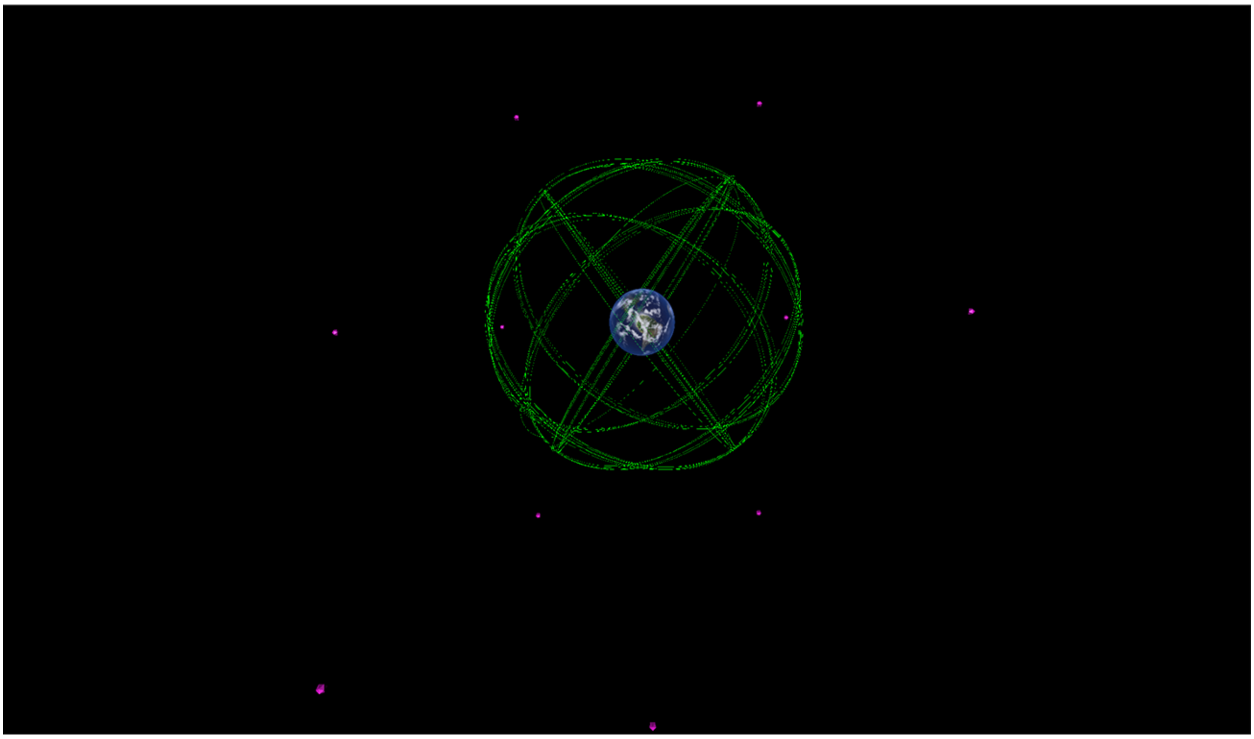


Figure 5.29: The trajectories of the GPS satellites.

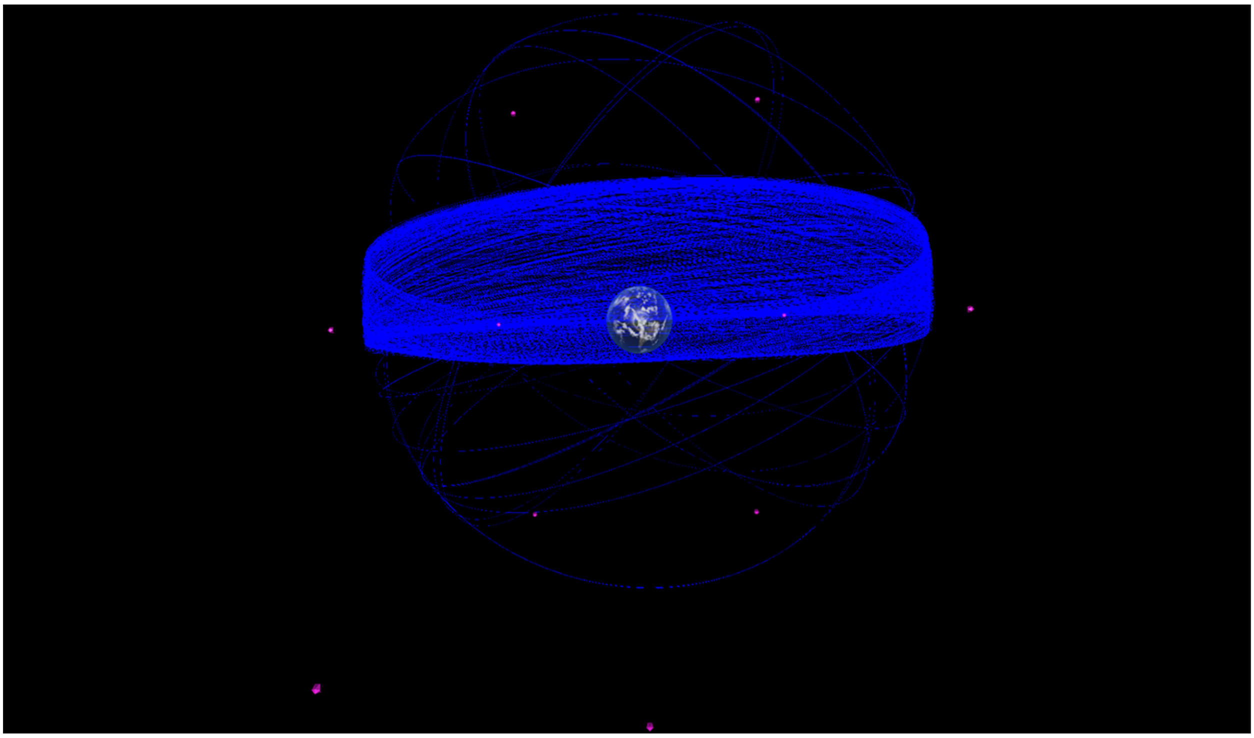


*Figure 5.30: The trajectories of the GEO satellites.*

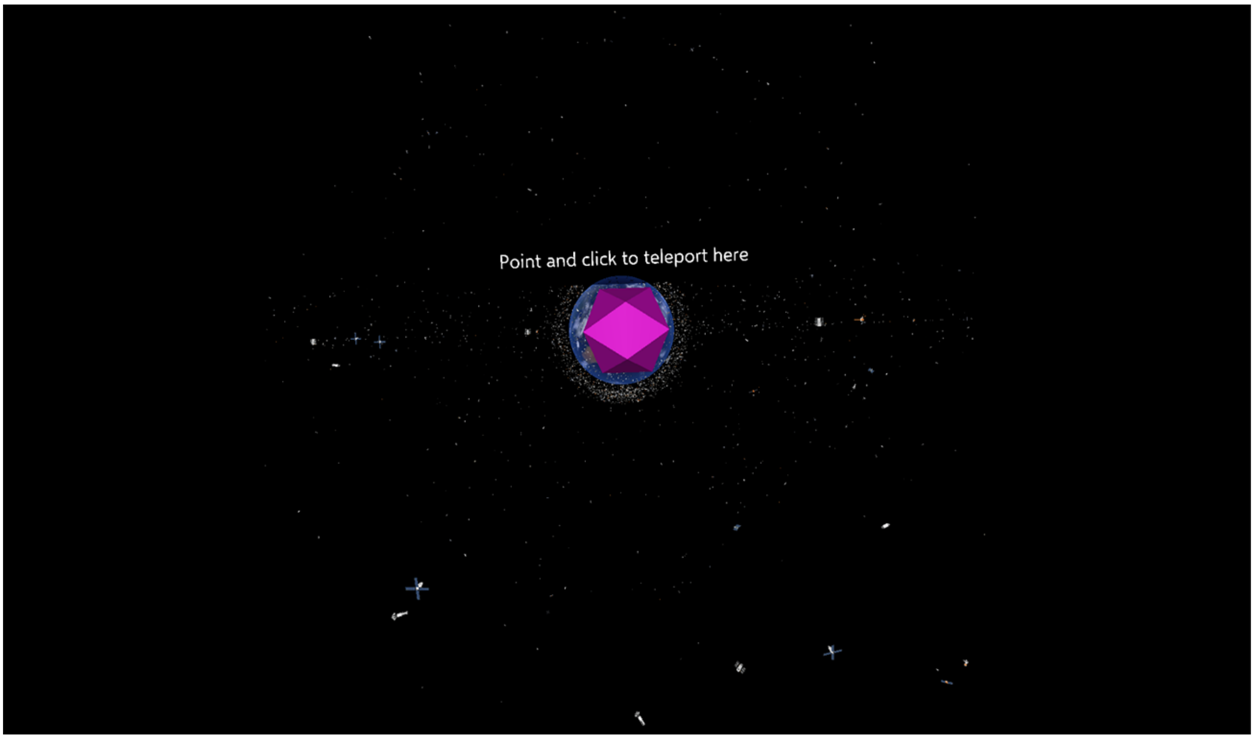


*Figure 5.31: The first step of the tutorial. Users are presented with a navigation landmark and a clue suggesting how to use it.*

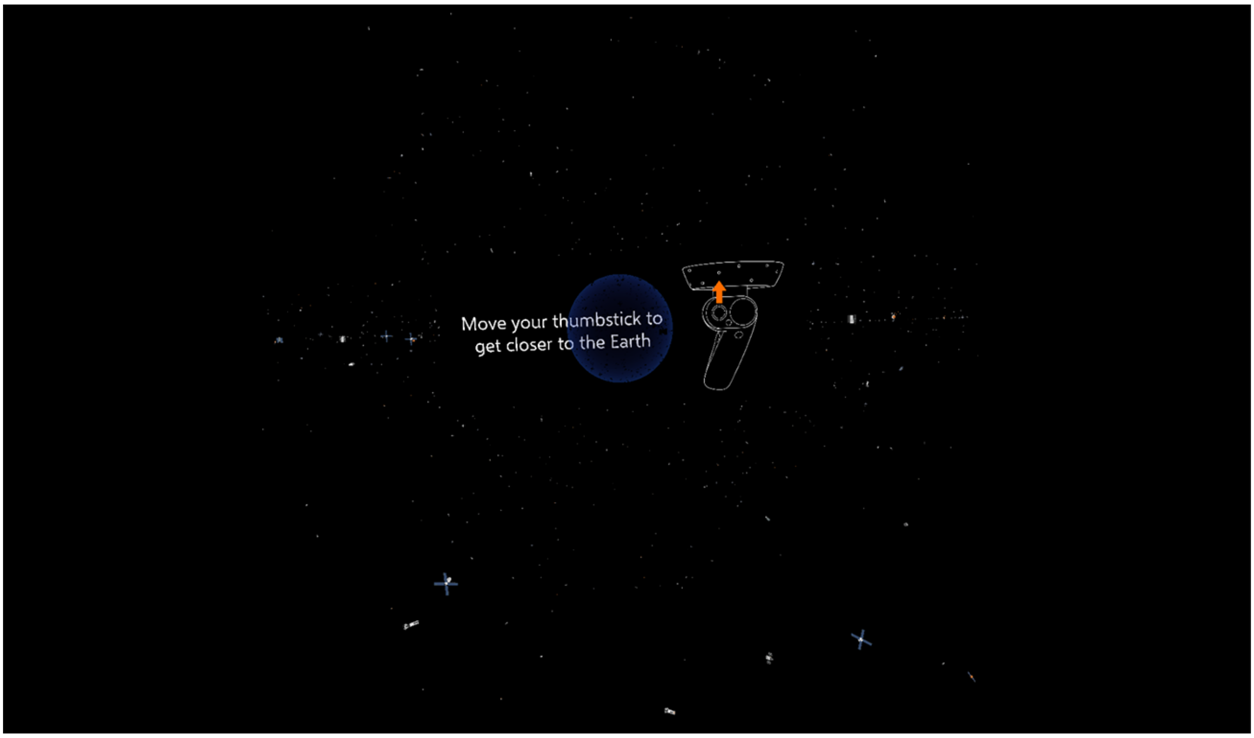


*Figure 5.32: The second step of the tutorial. Users are taught how to use the thumbstick to move closer to the Earth.*

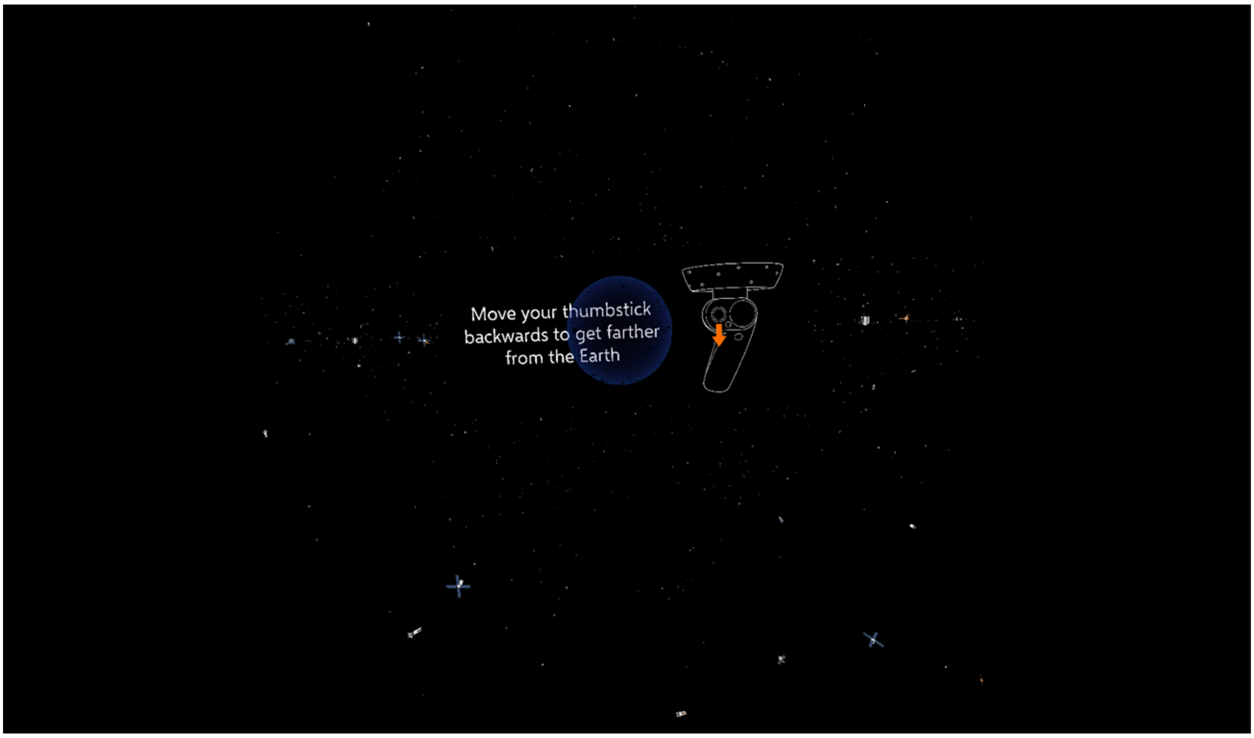
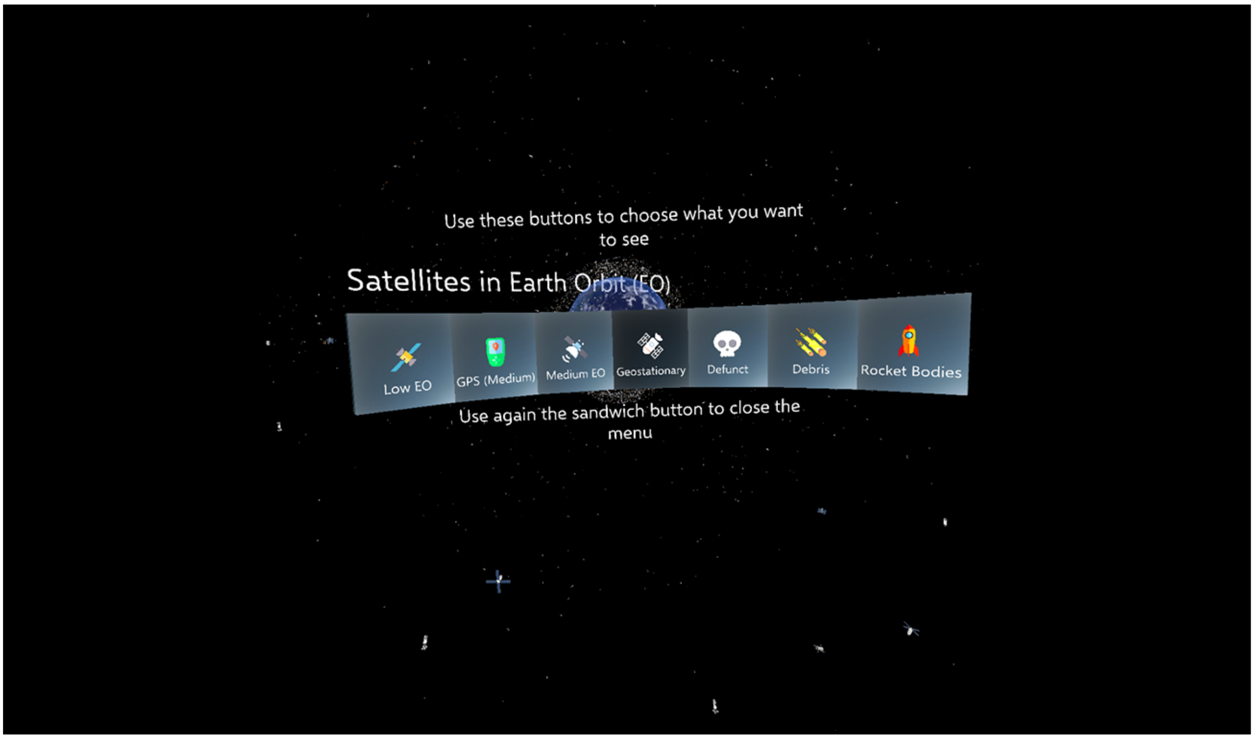


*Figure 5.33: The third step of the tutorial. Users are taught how to use the thumbstick to move farther to the Earth.*

Use the sandwich button to open and close the menu

Figure 5.34: *The fourth step of the tutorial. Users are taught how to open the menu.*



Use these buttons to choose what you want to see

Use again the sandwich button to close the menu

Figure 5.35: *The last step of the tutorial. Users are shown the menu, how to use it, and what to do to close it and start the exploration.*

# Chapter 6

# Experimental Results

This chapter presents the results of the preliminary evaluation of our application we performed during two events and one controlled experiment in our laboratory. We performed an initial evaluation during MeetMeTonight 2018, a dissemination event open to the public. The second evaluation was done during a closed event for journalists, start up companies, and people from Ministero dello Sviluppo Economico (MiSE). The final evaluation was performed in our laboratory with Master students attending the Video Game Design and Programming course.

## 6.1 Initial Prototype Evaluation

The first prototype envisioned users as astronauts who began their experience in the control room of a space station. They could read terminals displaying information about space debris and then they could head toward a "launch" door leading them to the outer space to begin their tutorial (Chapter 5). Then, they could start their exploration of space debris surrounding the Earth.

We showcased the first prototype during MeetMeTonight 2018 (September 28-29). Visitors were able to use the application for around 10 minutes. We did not ask people to fill in any questionnaire but just recorded their reactions to the experience that were overall very positive. During the event, we noted few problems. Firstly, people tended to pay almost no attention to the screens about space debris in the control room and had problems in locating the "launch" door. Furthermore, after launching, users skipped the initial part of the tutorial set in the Solar System and directly moved to the exploration part. Finally, the interaction with the menu and the controllers proved difficult for people with little experience in Virtual Reality (VR) or gaming in general. In the case of the controller, users had difficulties to see the laser pointer, especially when pointing far away, thus making aiming at navigation landmarks troublesome. The menu proved difficult for two reasons. First, the controller menu button used in Microsoft Mixed Reality headsets proved too small for inexperienced users. Second, the options the menu offered resulted unclear to people with no background knowledge on space debris who did not read the initial screens in the space station. Both issues were partly mitigated by providing a guided experience with a tutor using keyboard shortcuts to help users.

## 6.2 Second Stage Evaluation

The second prototype was substantially modified to improve the flow of users' experience. In particular, we completely revised the initial tutorial to focus on the application's main objective, that is, to raise awareness on the space debris problem. Accordingly, we eliminated both the space station control room and the Solar System experience, which users usually skipped, and presented space debris information in a more engaging way. We also extended the story to include additional information about satellites orbiting around the Earth and the evolution of space debris surrounding it. Users would begin their journey directly in space, facing the Earth. All the information previously provided by the terminals inside the space station were shown as text, appearing in front of the users, backed by the progressive introduction of satellites, payloads, and debris around the Earth. Then, users are introduced to the interactive landmarks used for navigation and, finally, their exploration experience can begin.

We presented the second prototype during a closed event for journalists, start up companies, and people from Ministero dello Sviluppo Economico (MiSE). We did not provide a questionnaire to fill. We just recorded the users' reactions to the experience and the questions posed before and after it. Overall, we received very positive feedbacks. Visitors were more accustomed to virtual reality and thus less fascinated by the media with respect to the ones visiting MeetMeTonight. People attending this event were more focused on the scientific implication of the experience, since they did not expect space debris to be such a threat for current and future space missions.

## 6.3 Evaluation with Students

We performed a final evaluation with Computer Engineering and Design Master students attending the Video Game Design and Programming course at Politecnico di Milano. Our goal was to test the application with more experienced users who were familiar with game controllers and possibly Virtual Reality devices. Each student received a short introduction to the experience and its scientific bases. Next, she would wear the headset and start her experience using the Story Mode (Chapter 4 and 5). At the end of the Story Mode, she would take a short navigation tutorial and then start the Exploration Mode. The experience lasted for around 15 minutes and at the end users were asked to complete an online form to evaluate their overall opinion.

The form comprised 25 questions, reported in Table 6.1. It was specified that when answers ranged from 1 to 5, 1 meant "very poor" and 5 meant "very good".

*Table 6.1: Questionnaire filled by the students for the experience's evaluation.*

| Id | Question | Answer Type |
|---|---|---|
| Q1 | Sex | Male/Female |
| Q2 | Experience with using videogames | One out of:<br>• Not at all<br>• Less than 2 hours per week<br>• Between 2 and 4 hours per week<br>• 7 hours per week<br>• More than 7 hours per week |
| Q3 | I did not have any problem with moving and activating things in the environment | True/False |
| Q4 | At first, I was uncomfortable in the environment, but after some moments moving and doing things was not a problem | True/False |
| Q5 | I could not manage to get really comfortable in the environment | True/False |
| Q6 | How would you rate the usability of the hand-held device | Range 1-5 |
| Q7 | How would you rate the usability of the 3D environment | Range 1-5 |
| Q8 | How would you rate the usability of the elements within the environment that can be activated/deactivated | Range 1-5 |
| Q9 | How would you rate the usability of the experience as a whole? | Range 1-5 |
| Q10 | Please add any comment/suggestion you deem useful | Open |
| Q11 | Did you find yourself comfortable in the experience as a whole? | Range 1-5 |
| Q12 | I felt comfortable at the beginning, but after some minutes I did not feel well | True/False |
| Q13 | I did not feel comfortable at the beginning, but after some moments I did well | True/False |
| Q14 | Please add any comment/suggestion you deem useful. It would be quite important to know what was MOST ANNOYING to you | Open |
| Q15 | How easy was it to understand the initial tutorial? | Range 1-5 |

| | | |
|---|---|---|
| Q16 | How easy was it to understand the panels meaning? | Range 1-5 |
| Q17 | How easy was it to understand the role of the orbiting objects | Range 1-5 |
| Q18 | How easy was it to understand the meaning of the trajectories? | Range 1-5 |
| Q19 | How easy was it to understand how the experience worked as a whole? (what the experience is about, where to go, what to do. . . ) | Range 1-5 |
| Q20 | Please add any comment/suggestion you deem useful. It would be quite important to know what was MOST UNCLEAR to you | Open |
| Q21 | In your perception, could this kind of experience enrich a traditional university lecture? | Range 1-5 |
| Q22 | Would you appreciate lessons with these kinds of enhancements? | Range 1-5 |
| Q23 | Overall, did you enjoy the experience? | Range 1-5 |
| Q24 | Please add any comment/suggestion you deem useful | Open |

The experiment involved 21 students (17 males and 4 females). One subject did not play video games; three played video games less than 2 hours per week; three played between two to four hours; three played between 4 and 7 hours per week; while 11 subjects played for more than 7 hours per week.

Most of the subjects did not have any problem with moving and activating things in the environment (Q3 received 16 true answers). Most of the students did not have any problem in the environment; the ones who had some initial issues solved them after a few moments of practice. 11 subjects answered true to Q4 but several who answered False then specified that they did not have any issue with the controls and therefore, because of their interpretation of Q4, answered false. This was confirmed by the answer to Q5 (16 false and 5 true), in which most of the students stated that they managed to get comfortable in the environment.

The subjects rated the usability of the controller, the environment, and the menu system as very comfortable—Q6 has an average of 4.14 and a median of 4; Q7 has an average of 4.23 and a median of 4; Q8 has an average of 4.09 and a median of 4. Overall the experience was also considered very intuitive and comfortable—Q9 has an average of 4.19 and a median of 4; Q11 has an average of 4 and a median of 4.

Motion sickness can be a major issue for virtual reality. In our case most of the students did not have any problem at all (16 out of 21 replied false to Q12) while 5 students had some light discomfort after some minutes. In fact, half of the subjects did not feel comfortable at the very beginning but felt comfy almost immediately.

Our application aims at raising the awareness about space debris and enhancing traditional lectures. The tutorial, the panels, the role of orbiting objects, and the meaning of the trajectories were easy to understand: Q15 has an average of 4.28 and a median of 5; Q16 has an average of 4.14 and a median of 4; Q17 has an average of 4.04 and a median of 4; Q18 has an average of 4.28 and a median of 4. The overall experience was also considered effective (Q19 has an average of 4.19 and a median of 4). The students deemed that this kind of experience could enrich traditional lectures and would appreciate lectures using these types of support: Q21 has an average of 4.47 and a median of 5; Q22 has an average of 4.47 and a median of 5. Overall, the experience was rated very positively (Q23 has an average of 4.42 and a median of 5).

In the open questions, we received some interesting suggestions. One student asked for dimmer colors which we plan to introduce as a special visualisation mode together with a colorblindness mode for accessibility. Students suggested that it would be interesting to add some information about the navigation status to the display (e.g., the position from the Earth) or physical forces (e.g., the gravitational field). A more experienced student suggested to include a free navigation mode, which we did not include since our preliminary tests showed that it dramatically decreases usability for most people. Two subjects noted that the visor did not fit comfortably.

# Chapter 7

# Conclusion

We designed, developed, and validated an educational application in Virtual and Augmented Reality to raise awareness about the space debris problem. Our application targets both people with some background knowledge about space missions (such as aerospace engineering students) and people with other backgrounds. In particular, it aims at supporting the course of "Orbital Mechanics" at Dipartimento di Scienze e Tecnologie Aerospaziali (DAER) of Politecnico di Milano. The target platforms were Hololens (Microsoft's Augmented Reality smartglasses), and ASUS Windows Mixed Reality Headset, a Virtual Reality head-mounted display. The application comprises a Story Mode and an Exploration Mode. The former is oriented towards the dissemination of information on the space debris problem to a general public. The latter targets a more experienced audience by allowing an educational stroll in near-Earth space.

We tested the first prototypes during two major events, MeetMeTonight 2018 (28-29 September) and a closed event for journalists, start up companies, and people from Ministero dello Sviluppo Economico (MiSE). In both cases we received very positive feedbacks and some useful suggestions on how to improve certain aspects of the experience. Then, we validated the last version of the application with a more experienced audience: Computer Engineering and Design Master students attending the Video Game Design and Programming course at Politecnico di Milano. Each student was given around 15 minutes to try the experience and, after that, was asked to fill in a questionnaire for its evaluation. Overall, the results (reported in Chapter 6) proved to be very satisfactory.

Virtual and Augmented Reality are effective means to engage people in captivating and interactive activities. Thanks to this, it is possible to exploit them to provide immersive experiences for educational purposes that are also fun and enjoyable.

Future research directions include the support to wireless Virtual Reality headsets like Oculus Go, to extend the roster of supported platforms. We are considering to move the rendering to the remote server. Finally, we plan to add "multiplayer" support to let students and instructors share the same experience.

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