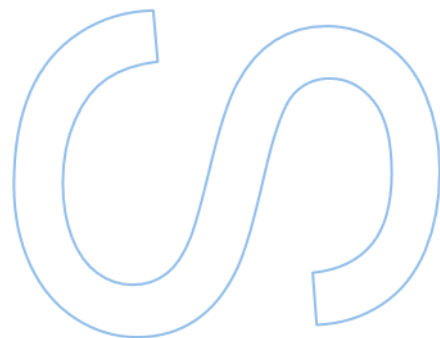
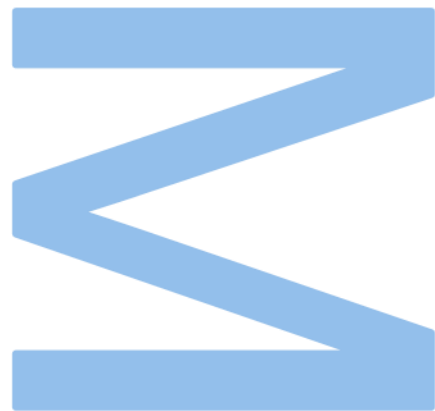


Enhancing Spectral Imaging Capabilities with Augmented and Mixed Reality

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Resumo

Esta tese apresenta um estudo da integração de *spectral imaging* com tecnologias de realidade aumentada e mista (AR/MR) para criar um ambiente interativo e imersivo dedicado à exploração e visualização de dados espectrais.

Spectral imaging é um termo que se refere a técnicas de espectroscopia que incluem espectroscopia de plasma induzido por laser, espectroscopia Raman e espectroscopia de refletância. Estas técnicas capturam as características espectrais de uma amostra, permitindo mapeá-las numa imagem 2D, revelando assim a sua natureza subjacente ao expor características como a composição química ou molecular, que são invisíveis a olho nu. Por outro lado, os avanços recentes na tecnologia possibilitaram o desenvolvimento de dispositivos capazes de expandir a nossa realidade, sobrepondo informações digitais ao mundo real e oferecendo um método de visualização que as apresenta de forma intuitiva e interativa. Embora estas tecnologias tenham finalidades distintas, ambas contribuem para uma extensão da realidade centrada no utilizador. Tirando partido destas oportunidades, este trabalho apresenta um conjunto de ferramentas de realidade aumentada e mista projetado para melhorar a interpretabilidade e interatividade dos dados espectrais, proporcionando uma ferramenta de análise mais acessível e abrangente.

Ao longo do projeto são descritas metodologias para a extração e análise de dados espectrais, geração de modelos 3D e desenvolvimento de uma interface no Unity. Os resultados são demonstrados em três projetos distintos. O primeiro projeto envolve uma interface que permite aos utilizadores explorar modelos 3D pré-carregados de amostras e correspondentes mapas espectrais, permitindo interações como *zoom* e rotação para uma exploração detalhada das suas características e propriedades. O segundo projeto faz uso de códigos QR para carregamento e interação em tempo real com amostras. Por fim, o terceiro projeto integra dados espectrais diretamente em objetos físicos, alinhando informações espectrais digitais com os seus equivalentes no mundo real para melhorar a interpretação contextual.

Estes projetos permitem, em conjunto, que os utilizadores visualizem e interajam com dados espectrais num ambiente 3D, melhorando a compreensão contextual dos resultados. Esta abordagem oferece um potencial significativo para aplicações em áreas como a educação, a indústria e a investigação, onde a capacidade de explorar informações espectrais detalhadas num ambiente imersivo pode apoiar uma tomada de decisão mais informada e uma compreensão mais profunda de fenómenos complexos.

Palavras-chave: Realidade aumentada, Realidade Mista, Imagem Espectral, Fotogrametria, Integração de Modelo 3D, Visualização Interativa

Abstract

This thesis studies the integration of spectral imaging with Augmented and Mixed Reality (AR/MR) technologies to create an interactive and immersive environment dedicated to the exploration and visualization of spectral data.

Spectral imaging, which includes techniques such as Laser-Induced Breakdown Spectroscopy, Raman spectroscopy, and reflectance spectroscopy, captures and maps the spectral characteristics of a sample onto a 2D image, uncovering the underlying nature of objects by revealing features such as chemical or molecular composition that are otherwise invisible to the naked eye. On the other hand, recent advances in technology have led to the development of devices capable of augmenting our reality by overlaying new information onto the physical world, offering a method of visualization that displays this information in an intuitive and interactive way. Although these technologies serve different purposes, both contribute to a user-centric extension of reality. Building on these opportunities, this work presents a mixed reality toolkit designed to enhance the interpretability and interactivity of spectral data, providing a more intuitive and comprehensive analysis tool.

Throughout the project, methodologies for extracting and analyzing spectral data, generating 3D models, and developing a user interface in Unity are described. The outcomes are demonstrated in three different projects. The first project involves an interface that allows users to explore preloaded 3D sample models and corresponding spectral maps, allowing interactions such as zoom, rotation, and pan for detailed exploration of features and properties. The second project makes use of QR codes for real-time loading and interaction with samples. Finally, the third project integrates spectral data directly onto physical objects, aligning digital spectral information with real-world counterparts to enhance contextual interpretation.

These projects collectively enable users to visualize and interact with spectral data in a 3D environment, improving the contextual understanding of the results. This approach offers significant potential for applications in fields such as education, manufacturing, and research, where the ability to explore detailed spectral information in an immersive setting can support more informed decision-making and a deeper understanding of complex phenomena.

Keywords: Augmented Reality, Mixed Reality, Spectral Imaging, Photogrammetry, 3D Model Integration, Interactive Visualization

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List of Abbreviations

LIBS Laser-Induced Breakdown Spectroscopy

HSI Hyperspectral Imaging

LIF Laser-Induced Fluorescence

HDF Hierarchical Data Format

ALSS Asymmetrical Least Squares Smoothing

VTK Visualization Toolkit

6DOF Six Degrees of Freedom

UWP Universal Windows Platform

MRTK Mixed Reality Toolkit

XR Extended Reality

AR Augmented Reality

VR Virtual Reality

MR Mixed Reality

HUDs Heads-Up Displays

HMDs Head-Mounted Displays

MEMS Micro-Electro-Mechanical Systems

2D Two-Dimensional

3D Three-Dimensional

1. Introduction

As humans, we rely on various biological systems and processes, known as **senses**, to gather information and perceive the world around us. These senses enable us to recognize faces, detect colors, hear sounds, and feel textures, but our biology inherently limits them. For instance, our vision is restricted to a small range of wavelengths within the visible portion of the electromagnetic spectrum, leaving a vast amount of information beyond our awareness. This limitation in visual perception means that many features and details present in the environment remain hidden. However, recent advancements in technology have provided tools that aim to overcome these biological constraints, enhancing human perception: **Spectral imaging** and **Extended Reality (XR)** are two of such technologies, working in unique yet complementary ways.

On one hand, spectral imaging harnesses the capabilities of spectroscopy techniques to capture data beyond classical RGB imaging and map it onto a Two-Dimensional (2D) image. Indeed, techniques such as Laser-Induced Breakdown Spectroscopy (LIBS), Hyperspectral Imaging (HSI), and Raman spectroscopy allow gathering detailed information about samples from the atomic to the molecular level, including the spatial distribution of chemical elements or sample composition. In this way, spectral imaging provides insights that are not visible to the naked eye, thereby offering a deeper understanding of the environment and enhancing the capacity to interpret complex samples.

On the other hand, Augmented Reality (AR) and Mixed Reality (MR) are technologies that aim to bring digital information into the physical world [1], unleashing the potential for immersive and interactive experiences and promising to exploit the full spectrum of human sensory perception to interact with digital data [2]. Indeed, traditional visualizations are often limited to 2D images, which pales in comparison to our native capability to process information in Three-Dimensional (3D) space.

In this thesis, and leveraging on the emerging work of INESC TEC in the field of spectral imaging in the last few years, we set to explore the synergy between these two tools, mapping the opportunities and challenges while paving for future solutions with impact from science to industry.

1.1. Seeing the Unseen with Spectral Imaging

Spectral imaging is a generic term that refers to the use of spectroscopy techniques to generate images representing spatially referenced signals from sample surfaces. Combining the spectral data obtained for each spatial point into a single dataset (see Figure 1.1), this approach offers a unique way to visualize and analyze spectral data, enabling the detection of features and properties of objects that are **otherwise invisible to the human eye**. Indeed, by examining the content of the generated images, and depending on the technique utilized, researchers can gain valuable insights into the composition (atomic or molecular) of the samples under study, allowing the development of tools for accurate analysis and informed decisions at academic and industrial levels [3–5].

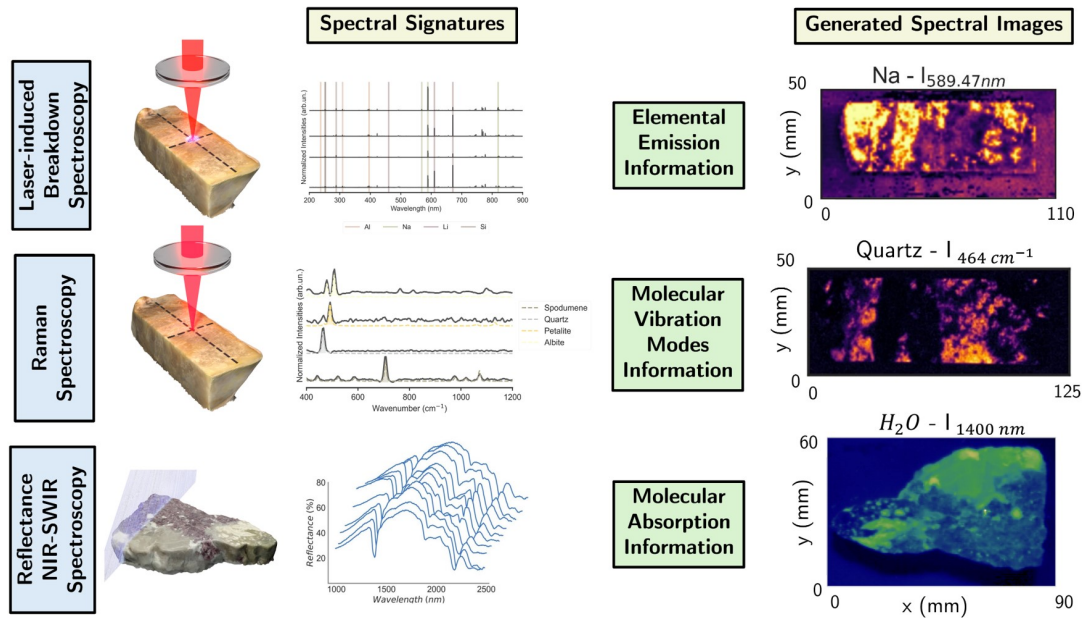


Figure 1.1: The information and type of signal obtained depend on the spectroscopy technique utilized.

There are numerous spectroscopy techniques capable of extracting valuable information from a wide range of samples, including, but non-limited to, Hyperspectral Imaging [6], Laser-Induced Breakdown Spectroscopy [7], Raman Spectroscopy [8], X-Ray Fluorescence [9], and Laser Ablation Inductively Coupled Plasma Mass Spectroscopy [10]. Each method is carefully chosen according to the specific characteristics of the samples to be analyzed and the intended application. For example, some of the most distinctive characteristics between various types of spectral imaging analysis encompass capabilities like sensitivity and speed, as well as other features such as allowing for in-situ and remote operation [7]. Another relevant characteristic may be the requirements at the sample preparation level (i.e. minimal or non-minimal) or the damage of the technique (e.g.

destructive or non-destructive analysis), especially relevant for industrial applications or critical applications at the academic level [4, 11]. Among the various spectroscopy techniques, the team at the Centre for Applied Photonics at INESC TEC has been exploring mainly three techniques: Hyperspectral Imaging (HSI), Laser-Induced Breakdown Spectroscopy (LIBS), and Raman Spectroscopy.

HSI leverages on the analysis of the reflectance spectra of a sample surface, and can cover a multitude of ranges from UV-Visible to Near-infrared, short-wave infrared, and even long-wave infrared. Regarding its most important features, HSI stands as an exceptionally fast technique, utilizing a push-broom configuration to scan a sample surface line-by-line and quickly generate detailed spectral data. A typical spectral signature comes with absorption bands (see Figure 1.1) which may be related to the presence of molecular bands in the sample, making HSI a valuable tool for material identification and analysis, with many applications from industrial [5] to remote [12] scenarios.

LIBS is another powerful spectroscopy technique, which will be particularly significant to this project. This analytical method uses a high-energy laser pulse to ablate a small portion of a surface, creating a plasma that emits radiation as it cools [7]. By analyzing the emission lines from the obtained spectrum (see Figure 1.1) and relating them to specific element emission lines, LIBS enables the determination of the elemental composition of the sample. The major advantages of LIBS include its robustness and potential for *in situ* and remote analysis (instrumentation portability), minimal sample preparation, robustness to environmental noise, and possibility of remote operation [13]. For this reason, LIBS is popular for applications in critical and harsh environments, such as underwater [14] or space [13] environments, with the integration of LIBS instruments in rovers for planetary surface analysis being one of the most notable examples. Furthermore, as LIBS provides such a vast amount of information, it is typically combined with machine learning and artificial intelligence algorithms to deploy solutions for accurate sample classification [15] and even quantitative analysis [16, 17], providing better insights of the sample constituents. However, in the specific context of spectral imaging applications, LIBS features as a major drawback its operation using a point-by-point scanning method, also known as whiskbroom scanning, making it slower than HSI for example.

Finally, **Raman Spectroscopy** is another noteworthy technique that relies on the inelastic scattering of light - known as Raman scattering - to gain insights into the molecular

structure of the sample. In particular, the spectral bands observed in the Raman spectroscopy signal can be analyzed against reference ones for the identification of chemical compounds [18] and detailed analysis of molecular structures, especially in crystalline materials [19], which is perhaps its best advantage. Similar to LIBS, Raman also uses a point-by-point scanning method to provide a molecular fingerprint. In addition, due to the low intensity of the scattering signal, the integration time necessary to acquire each spot is typically around hundreds of milliseconds, making operational equipment even slower than LIBS, which constitutes its major drawback.

1.2. Enhancing human-data interaction through Extended Reality

XR is an umbrella term that encompasses a range of immersive technologies, including AR, Virtual Reality (VR), and MR (Figure 1.2), each contributing uniquely to the potential transformation of various industries, from education and engineering to medicine and beyond. Although distinct in their characteristics, these technologies share in common the ultimate goal of enhancing users' perception and interaction with digital data and models, reflecting the extension of human capabilities by leveraging the intersection of the physical and digital worlds [2].

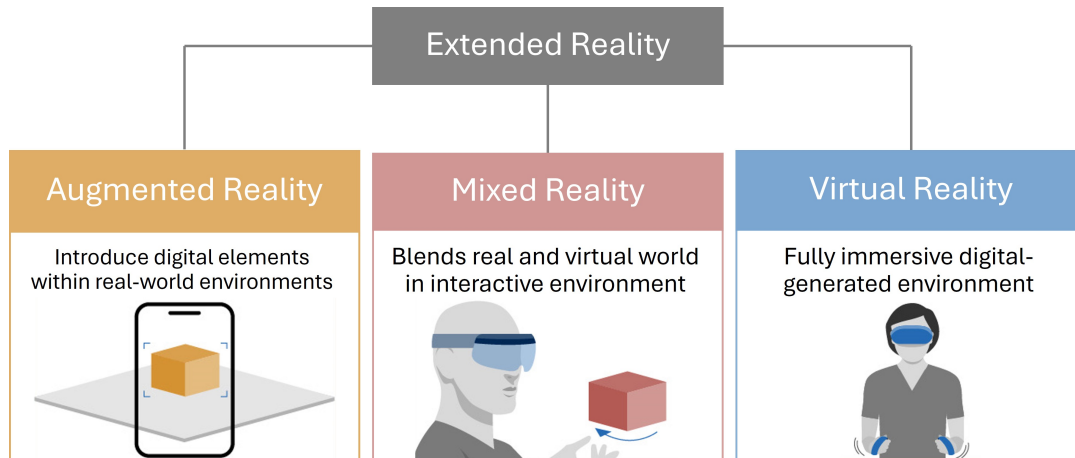


Figure 1.2: Extended reality diagram outlining its categories with brief descriptions. (Adapted from [20])

Starting with Virtual Reality, it distinguishes itself from the others in the fact that the user experience occurs in an environment that is totally virtual, with no relation to the real world. In this case, the user is surrounded by computer-generated visual effects and sounds, cutting off the user from the real world and creating a fully controlled and virtual experience [21]. The origins of Virtual Reality technology can be traced back to 1956, when cinematographer Morton Heilig developed the *Sensorama* [22] (Figure 1.3). The

device allowed users to watch short films while experiencing synchronized sensory effects, simulating the feeling of being physically present in the scene [23, 24]. The size and the lack of user interaction with the virtual environment were the major limitations of the device, which sparked further research to target these obstacles. The term *Virtual Reality* was popularized later in 1987, with the significant contribution of Jaron Lanier, founder of VPL Research [23], through the development of some of the first commercial VR systems, including data gloves and VR headsets. Nowadays, these devices allow users to experience and interact with fully virtual environments, providing an innovative level of immersion, and find applications in manufacturing process simulation [25], helping reduce the time and cost involved in taking a product from conceptualization to production; in military training, offering a safe yet realistic way to simulate combat training scenarios [26] or practice in flight environments (vehicle and aircraft simulations) [27]; and even in entertainment [28], where immersive gaming experiences and virtual worlds, driven by multi-sensory immersion, interactivity, and imagination, are gaining widespread popularity.



Figure 1.3: First virtual reality device called *Sensorama*. (Adapted from [22])

A bit distinct from VR, Augmented Reality centers around the idea of overlaying digital information onto the real world, maintaining a continuous connection with the physical environment. This approach allows users to engage with digital models and data in

real-time within their actual surroundings, creating a more immersive and interactive experience [29]. Even though it is possible to trace earlier examples in which information was layered over the physical world, the incorporation of computer-generated elements and digital data into our world without interaction began in 1968, when Ivan Sutherland developed the first head-mounted display system [1, 22]. This system, referred to by its



Figure 1.4: First optical head-mounted display built-in 1968 by Ivan Sutherland. (Adapted from [1])

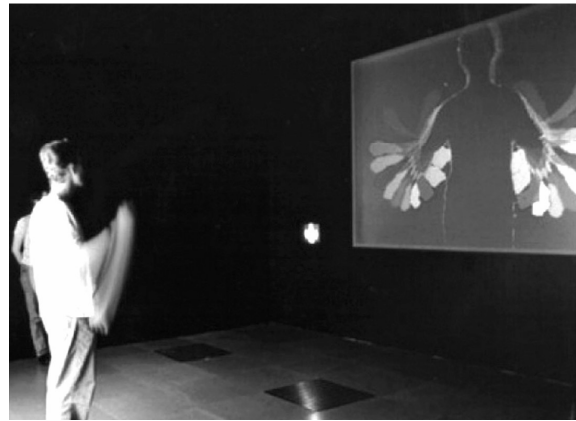


Figure 1.5: Scene from the Videoplace interactive art system. (Adapted from [22])

creators as a *Stereoscopic-Television Apparatus for Individual Use* (or also jokingly called *The Sword of Damocles* due to its mechanical apparatus), is considered the first step towards AR, using an optical see-through head-mounted display to show virtual graphics, and allowing for user interaction with Six Degrees of Freedom (6DOF) trackers (Figure 1.4). The term *Augmented Reality* was later coined by Tom Caudell and David Mizell [30] in 1992, redefined later by Ronald Azuma [31] as a system featuring three characteristics: i) combines real and virtual; ii) interactive in real time; iii) registered in three dimensions (Figure 1.6). These days, AR is perhaps the most popular form of XR, being commonly used for displaying information in vehicles using heads-up displays [32], providing interactive gaming experiences (e.g. Pokemon Go), or even as an assisting tool for the retail market (e.g. IKEA, Adidas), just to mention a few examples. Closer to scientific research, AR also finds many applications in the field of medicine. For example, the use of AR as a surgical tool [33] may assist in planning and guiding stages via a hologram projected onto the patient in real-time [34].

Finally, Mixed Reality, blends aspects of AR and VR, allowing for a deeper fusion between the physical and virtual worlds by integrating virtual elements onto physical objects that

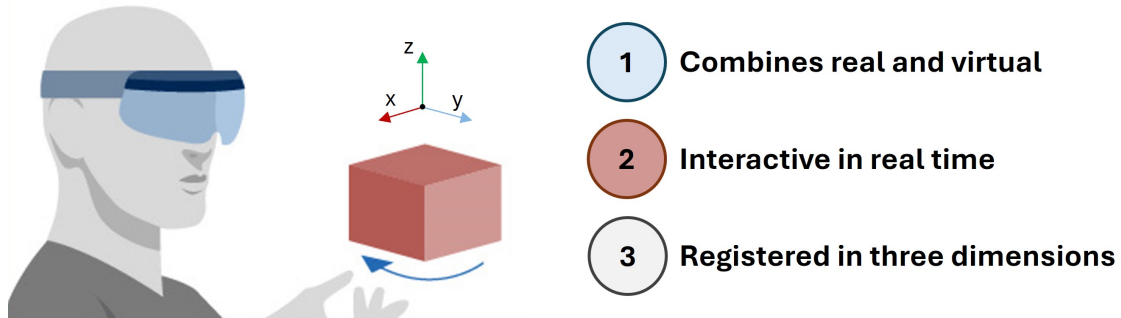


Figure 1.6: Schematic demonstrating the key features of Augmented Reality.

users can touch, move around, and interact with in real-time, creating a seamless and interactive experience. In other words, the digital data interacts with the real world and is not only superimposed on top of it. One of the major hallmarks of user interaction dates back to 1975, when Myron Krueger created *Videoplace* (Figure 1.5), marking one of the earliest and most well-known attempts to deploy an interactive environment where users could interact with virtual objects without the need for physical equipment like goggles or gloves [35]. This system used cameras to capture the silhouette of the user in real-time, which was then projected onto a large screen. The virtual objects, which were computer-generated images also projected onto the screen, were programmed to respond in various ways to the movements of the user. For example, if the user moved their hand towards a virtual object, the system would recognize this movement and simulate an interaction, such as pushing or grabbing the object, marking a significant advancement in the interaction between the physical and virtual worlds. Another significant milestone in MR was the release of the Microsoft HoloLens in 2016. As we will later discuss in detail in this dissertation, this head-mounted display is assisted with a multitude of sensors that enable users not only to see but also to interact with 3D holograms in the physical space around them. Besides, benefiting from the advancement of user-friendly development tools such as Unity Platform, the number of applications has increased significantly in the last decade, sapping diverse fields from education [33, 34] to medicine [36–40], to manufacturing and maintenance [41, 42] or industry [43].

1.3. Convergence of Spectral Imaging and Extended Reality

As discussed previously, Spectral Imaging and Extended Reality converge in the way these technologies enhance human perception, *allowing us to see what our eyes cannot*. So it is straightforward to ask for a solution that combines both into a single solution.

Indeed, and in conceptual terms, spectral imaging holds the potential to provide novel layers of information that may in principle benefit from XR technologies to be superimposed onto digital models or even real-world objects, ultimately allowing users to see beyond human vision and enabling deeper analysis and better insights into the data [44, 45]. Some pioneering results in the literature already hint in this direction, either utilizing projection methods [46] or interactive headsets, with the latter significantly enhancing the experience via additional embedded sensors. For example, ref. [45] explores the combination of a fiber optic Raman probe and an augmented reality localization strategy and interface to create a visualization of a chemical image of samples, overlaid yet not anchored to the physical object. Examples with hyperspectral imaging include medical applications such as the classification of tissues during in-vivo surgical procedures [47] and a toolset for guided brain tumor phantom resection which utilizes a HoloLens AR headset [44], to mention a few illustrative examples. In the geological sciences domain, a topic of particular interest for INESC TEC team, ref. [48] presents an interesting toolset to analyze rock surfaces and mineral types, which may be promising to assist in-situ operations, but again missing contextual interpretation of 3D models. In this regard, the previous work by our team on seamless integration of spectral imaging datasets with scanned 3D digital models of the sample[3] opened a window of opportunity for interactive and contextual analysis, although its first version was limited to analysis on a computer screen.

In general, even though these approaches demonstrate the potential of combining XR and spectral imaging, the full potential of the merging of both techniques is often overlooked. To the best of our knowledge, by the starting date of this MSc dissertation work, no toolset was available to fuse interactive 3D digital models with spectral imaging in XR environments. Besides, capabilities such as arbitrarily scaling of the samples to enhance details, access to other perspectives, or interactively exploration of spectral information were also overlooked in previous approaches, even though they carry additional value for the end-user, enhancing the productivity and effectivity of the experience.

1.4. Objectives

As discussed, although combining spectral imaging tools with XR technologies encloses major potential for impactful academic and industrial applications, there are very few approaches and tools capable of visualizing such type of data while simultaneously observing and interacting with the environment. Existing solutions often require the use of a

computer or smartphone to interpret spectral characteristics, hindering mobility and preventing seamless integration of spectral information into our immediate perception.

In this context, this work aims to take a step forward in bridging this gap by enabling the visualization of data in our reality, regardless of our position, by making use of an AR and MR device - the **Microsoft Hololens 2**. Thus, this thesis presents itself as the first step towards a new generation of user-centric tools on the topic of spectral imaging, capable of integrating spectral data into our perception of the real world through the use of Augmented and Mixed Reality methodologies. This vision materializes in two operational objectives:

- **Develop a processing pipeline and AR toolset for spectral imaging:** a full-stack solution that is capable of combining spectral imaging datasets with 3D models, before displaying them in augmented reality environments, aiming to create an immersive toolset to increase the interpretability and interactivity of the results of spectral imaging analysis; and establish the first steps towards a streamlined utilization: load, move, and position 3D models along with their respective spectral data using real-world anchors and assets (e.g. QR codes);
- **Develop a processing pipeline and MR toolset for spectral imaging:** Recognize a real three-dimensional sample to enable the superimposition of its spectral information directly onto it. Note that this is a solution that goes beyond AR in the way it interacts with real objects;

1.5. Document structure

The structure of this dissertation divides itself into six chapters as follows.

Chapter 1 explores the potential of spectral imaging and XR technologies to enhance human visual perception. It begins by providing an overview of various spectroscopy techniques capable of generating spectral images, alongside a contextual introduction to XR. Additionally, it discusses the convergence of Spectral Imaging and Extended Reality in general terms, concluding with the project's objectives.

Chapter 2 delves into the Laser-Induced Breakdown Spectroscopy technique as a source for generating spectral images, explaining its theoretical foundation, a typical experimental setup, and the essential steps involved in processing LIBS data for qualitative analysis. In the latter half, a pipeline is introduced to generate 3D models through photogrammetry and fusion them with spectral images.

Chapter 3 presents different types of devices capable of delivering XR experiences, highlighting their key features and capabilities. It then focuses on the specific device used in this project, the HoloLens 2, detailing its features, specifications, and applications. The chapter concludes by exploring the configuration software methodology, with an emphasis on the Unity engine and the Mixed Reality Toolkit.

Chapter 4 details the methodology employed to develop an augmented reality software solution, including a description of the samples studied and the results of applying an alignment algorithm. The chapter then presents two interfaces that showcase the potential of combining spectral imaging with Extended Reality and concludes with a critical discussion of possible application scenarios and the impact on future explorations.

Similarly, Chapter 5 presents the results of an interface, now applied in the context of mixed reality, accompanied by a concise discussion.

Finally, Chapter 6 wraps up the work, summarizing the findings and discussing potential future work that integrates all the developed projects.

1.6. Thesis outputs

Journal Publications:

- "Beyond Human Vision: Unlocking the Potential of Augmented Reality for Spectral Imaging", Rafael Cavaco, Tomás Lopes, Diana Capela, Diana Guimarães, Pedro A. S. Jorge, Nuno A. Silva, *under revision*
- "Interactive three-dimensional chemical element maps with laser-induced breakdown spectroscopy and photogrammetry", Tomás Lopes, Pedro Rodrigues, Rafael Cavaco, Diana Capela, Miguel F.S. Ferreira, Diana Guimarães, Pedro A.S. Jorge, Nuno A. Silva, *Spectrochimica Acta Part B: Atomic Spectroscopy*, Elsevier. (2023)

Conference Proceeding:

- "Augmented Reality for Spectral Imaging Applications", Rafael Cavaco, Tomás Lopes, Pedro A.S. Jorge, and Nuno A. Silva, *Proceedings of SPIE Photonics Europe - Unconventional Optical Imaging IV*. (2024)

Oral Presentations:

- "Augmented Reality for Spectral Imaging Applications", Rafael Cavaco, Tomás Lopes, Pedro A.S. Jorge, Nuno A. Silva, IJUP2024 - Young Researcher Meeting of University of Porto. (2024)
- "Mixed Reality Meets Spectroscopy: Interactive 3D Visualization of Spectral Signatures", Rafael Cavaco, Tomás Lopes, Pedro A.S. Jorge, Nuno A. Silva, AOP - Conference on Applications of Optics and Photonics. (2024)

Poster Presentations:

- "Augmented Reality for Spectral Imaging Applications", Rafael Cavaco, Tomás Lopes, Pedro A.S. Jorge, and Nuno A. Silva, Proceedings of SPIE Photonics Europe - Unconventional Optical Imaging IV. (2024)

2. Spectral imaging: From 2D images to 3D models

Spectral imaging has become an indispensable analytical tool for academic and industrial applications, allowing for fast and critical insights into the elemental composition of analyzed samples. Traditional spectral imaging comes in the form of 2D images, meaning that it would not benefit greatly from the use of XR tools. Yet, when projected into digital 3D models, it may unleash a new array of opportunities under XR environments.

In light of this, this chapter offers a concise overview of the theory behind spectral imaging focusing on the specific technique of Laser-Induced Breakdown Spectroscopy, introducing the technique and setup utilized in this work, discussing its major features, and briefly explaining the typical workflow for qualitative analysis of LIBS data. In the second part of the chapter, we introduce a processing pipeline to merge the LIBS images into 3D models generated via photogrammetry, detailing a method for model alignment, which is crucial for accurately overlaying spectral data onto three-dimensional models.

2.1. An Overview of LIBS spectroscopy

LIBS is a powerful analytical technique that utilizes a high-energy laser pulse as an excitation source to analyze the atomic composition of materials. In this method, a short-duration pulsed laser beam (typically a few nanoseconds, but pico and femtosecond can also be utilized) is focused at a specific spot on the sample surface layer delivering an intense energy localized within a few hundred micrometers (Figure 2.1).

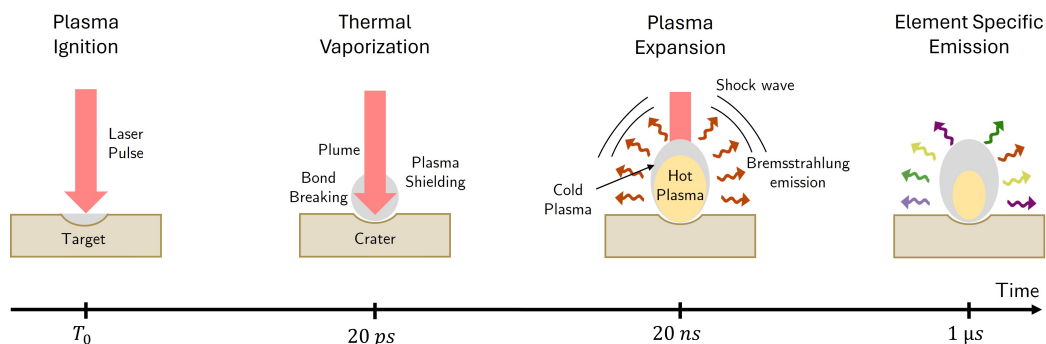


Figure 2.1: Representation of laser-matter interactions in LIBS with approximate timescales.

This high energy density causes an intense rise in the temperature at that spot, rapidly exceeding the boiling point of the material, and leading to its ablation and vaporization. Still

absorbing energy from the laser pulse, this gas keeps heating until it attains a dielectric breakdown threshold, forming a plasma plume composed of ionized atoms and electrons [7].

As soon as the laser ends, the plasma (typical temperatures around 10000K) starts to cool down, and recombination and decaying processes start, emitting energy in the form of radiation. The emission varies over time and begins with a continuous emission of radiation (background emission), followed by ionic, atomic, and finally molecular radiation, as shown in Figure 2.2.

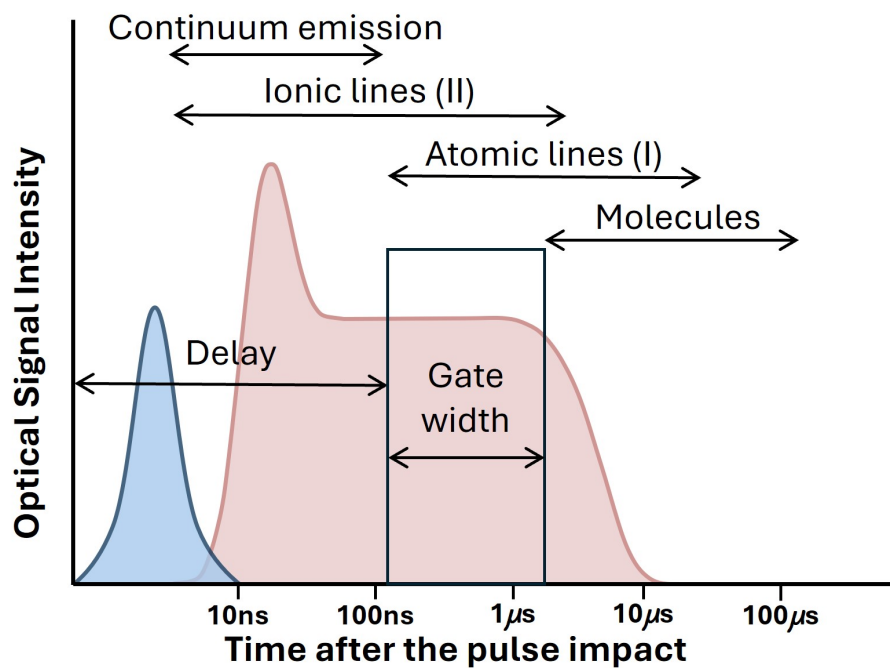


Figure 2.2: Graph illustrating the temporal evolution of plasma emission following a laser-induced breakdown. Data collection typically focuses on a small time window (gate width) that captures the atomic line region.

The background radiation is typically the first to appear and mostly comes from Bremsstrahlung radiation. This radiation arises from the deceleration of free electrons as they interact with ions in the plasma, and manifests as a continuous signal overlaying the entire spectrum, being thus unspecific and sometimes making it difficult to distinguish the true emission lines of the elements of interest. In later stages of plasma decay, the radiation is more interesting: internal transitions of electrons from excited states to ground levels of atomic, ionic, and even molecular species, emit light at very characteristic wavelengths due to the energy quantization of the electronic energy levels. Consequently, by analyzing this discrete emitted light spectrum, it is possible to determine the atomic composition of the material with high precision.

Compared to other techniques, LIBS offers several distinct features and advantages:

- Capability to detect (theoretically) all elements, including lighter ones, with sensitivity ranging from parts per million (ppm) to parts per billion (ppb);
- Ability to simultaneously detect multiple elements;
- Replaces a physical device (such as electrodes) with a laser to generate plasma, which:
 - Enables analysis regardless of the substance or its state (gas, liquid, or solid);
 - Requires minimal to no sample preparation;
 - Operates under extreme conditions, such as vacuum, underwater, and high temperature or pressure environments;
 - Achieves high-speed measurements, up to kilohertz rates;
 - Allows for remote (non-contact) analysis, facilitating the development of portable instruments and real-time analysis;
 - Causes limited and highly localized damage to the sample surface, almost non-destructive at levels of tens to hundreds of nanograms, making it suitable for applications in cultural heritage and artwork conservation;
 - Supports in-depth profiling;
- Additionally, its compact design allows for easy integration with other spectroscopic techniques, such as Raman spectroscopy, Laser-Induced Fluorescence (LIF), or hyperspectral imaging, enabling innovative sensor fusion solutions for industrial applications.

2.1.1 A typical LIBS Experimental Setup

A typical LIBS setup can be divided into a few operating modules, all of them centrally controlled and integrated with a computer (see Figure 2.3). For the experimental procedures of this work, we utilized a LIBS setup prototype previously designed in-house by our team at INESC TEC that we will subsequently describe in terms of major characteristics.

The first module concerns the laser, which is typically a pulsed laser within the femtosecond to nanosecond range. In particular, the core of our system is a Nd:YAG laser with an

operation wavelength of 1064 nm (Quantel) that serves as the excitation source, delivering short (10 ns) and high-energy (around 51 mJ with a repetition rate up to 20 Hz) pulses that ablate the sample material and ignite the plasma formation.

The second module is the optical apparatus that steers and focuses the laser beam on the sample. This is achieved with a plano-convex lens with a focal length of 20 cm with anti-reflective coating at 1064 nm to avoid damaging the laser. Note that since the focus is not variable, it is preferable to analyze planar surfaces to ensure optimal ablation and plasma formation.

Indeed the third module accounts for this distance by adding translation stages to position the sample. Our prototype features a precision of 10 μm and a total range of 10 cm that enables precise movement of the sample in the two transverse directions, conducting point-by-point scans of the sample surface. The third dimension is controlled using a manual vertical stage with micrometer precision that allows fine adjustments along the vertical axis, positioning the sample surface closer to the focal spot. To assist in this procedure, an integrated pointer system provides visual feedback to better position the sample at the focal spot.

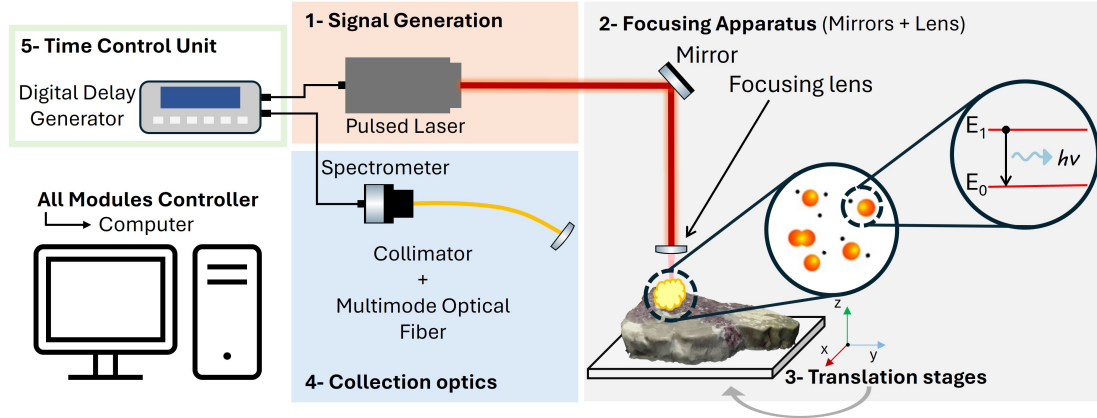


Figure 2.3: The schematic diagram of the LIBS experimental apparatus.

The fourth module intends to capture the emitted spectra, consisting of an optical collection system (a simple collimator connected to a multimode optical fiber with 600 μm of diameter) which delivers the signal to the instrument that performs the spectral analysis, i.e. the spectrometer. In our case, we utilize a set of eight spectrometers (Avantes AVASPEC-ULS2048-USB2-RM) to cover a broad spectral range from 180 nm to 920 nm.

Finally, the fifth module accounts for the time synchronization of all laser and spectrometer, allowing to precisely control the acquisition of each single plasma as well as, adding the

necessary gate delay to minimize the bremsstrahlung background radiation (around 500 ns). For this we utilize a digital delay generator (ATOMTRACE AC-DDG-4) that emits triggers with high temporal resolution (typically within nanosecond range) for both the laser and spectrometer.

All these modules are controlled with the computer via a set of in-house developed Python scripts and libraries to perform single-spot and multi-spot analysis across a multitude of geometries, as well as handling the datasets that are stored into a Hierarchical Data Format (HDF).

2.1.2 Qualitative Analysis with LIBS and Spectral Imaging

Generating a plasma and acquiring a spectral signal has its complexities but the subsequent analysis of the acquired data is equally important and perhaps even more challenging. In generic terms, we can divide LIBS analysis into three major families: i) quantitative analysis, where one tries to provide an estimate of the concentration of a given chemical constituent; ii) semi-quantitative analysis, where one tries to provide a range for the concentration of a given chemical constituent; or iii) qualitative analysis, where one provides qualitative insight on the presence or absence of chemical species, and that can also be used for further classification of the sample. For the purpose of this work, we will focus only on qualitative analysis with LIBS, but further information on the other applications can be found in ref. [7].

Typically, qualitative spectral data analysis in LIBS involves identifying the presence of specific elements within the sample by examining the characteristic emission lines in the spectrum.

Yet, due to the presence of unspecific background radiation, the process should start with a convenient data preprocessing workflow. Indeed, due to the presence of background radiation and instrumental noise (see Figure 2.4) raw data obtained from LIBS typically undergoes a two-stage preprocessing routine for better and more accurate results, effectively preventing the risk of missing important elements or falsely identifying noise as a meaningful signal:

- First, to address the challenge posed by background noise, techniques such as

baseline removal [49–51] or filtering [52] can be employed. In generic terms, baseline removal algorithms subtract the background signal from the spectrum, effectively “flattening” the baseline and allowing the true spectral peaks to be more easily identified and analyzed. For the purpose of this work, we will utilize an Asymmetrical Least Squares Smoothing (ALSS) algorithm [49], which is particularly effective at flattening the baseline and enhancing the visibility of the spectral lines corresponding to the elements in the sample.

- Secondly, to mitigate high-frequency noise. This type of noise, often stemming from instrumental limitations (e.g. dark current and thermal noise of the detector, among others), is characterized by rapid, small-scale fluctuations in the spectral data. Such noise can obscure weak emission lines, leading to false positives in peak detection and hindering accurate spectral interpretation. To address this, various smoothing techniques can be applied to reduce noise while preserving the integrity of the spectral feature including fitting to a polynomial function of neighboring spectral channels (such as Savitzky–Golay approach [53]), as well as Fourier transform-based filters [54].

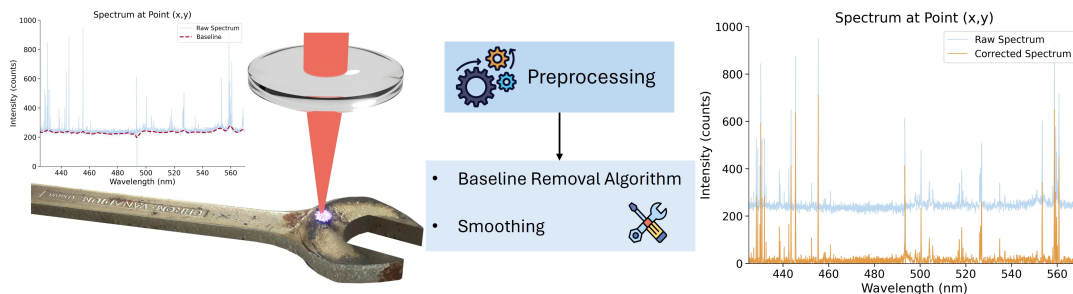


Figure 2.4: Visualization of the spectrum captured before and after preprocessing using baseline removal and smoothing algorithms.

After preprocessing the dataset, a qualitative analysis workflow proceeds by taking each spectrum and comparing it against known reference spectra or databases [55], such as the NIST dataset [56]. Indeed, each chemical element emits light at specific wavelengths when it transitions from an excited state back to its ground state, producing a distinctive spectral fingerprint. By matching the observed emission lines (often facilitated by numerical algorithms for peak identification) with those of known elements, it is possible to identify the elements present in the sample by following a user-defined criterium (typically finding 2 or 3 of the most relevant emission lines for the target element).

2.1.2.1 LIBS Imaging

LIBS imaging can be considered as a type of qualitative analysis where the objective is to scan a sample surface point-by-point trying to construct images related to the spatial distribution of chemical elements. In this manner, each experiment generates a 3D dataset with dimensions $N_x \times N_y \times N_\lambda$ as depicted in Figure 2.5. Here, $N_x \times N_y$ represents the two transverse spatial dimensions, while N_λ corresponds to the spectral dimension of the emission wavelengths, depending on the resolution and range of the spectrometers. For each specific wavelength, a characteristic 2D map of the sample, known as a spectral image, can be generated by mapping the intensity values at each spot.

Of course, to obtain valuable insight from this dataset, the primary objective of such analysis is to identify a wavelength that is related to the spatial structures or hidden features within the sample. This selection of relevant wavelengths can be guided by prior knowledge of the sample's composition (if available) or by searching for spectral lines with high intensity in the average spectrum or significant intensity variation between the minimum and maximum spectra, indicating the relevance of those spectral lines in the sample.

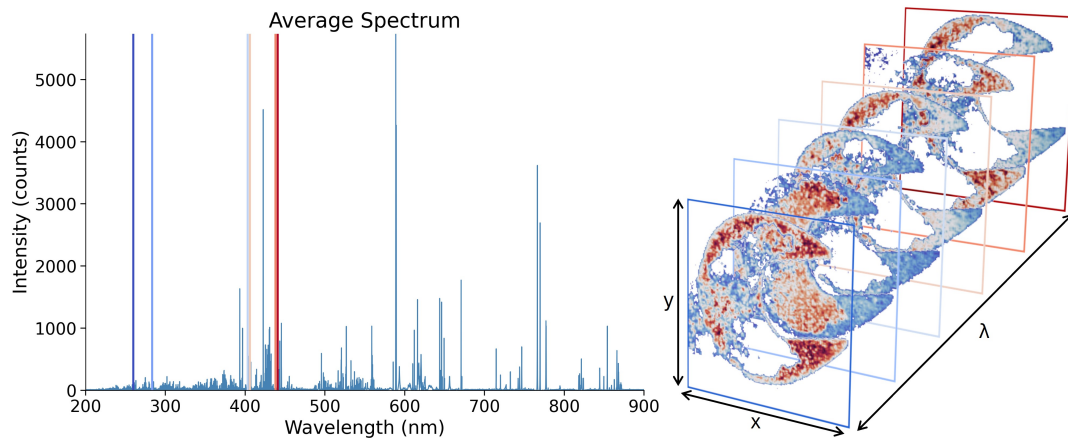


Figure 2.5: (Left) Average spectrum of all the spots targeted by the laser. (Right) A set of spectral images representing features of the sample under study.

One key application is the generation of elemental maps, which display the spatial distribution of element intensities within a sample, or even the creation of dispersion maps of elements and minerals, which offer an estimation of the spatial distribution of elements/minerals across the sample, aiding in geological and mineralogical analysis of complex materials (Figure 2.6 A, B, and D).

Due to the possibility to generate 2D images that reproduce valuable information about the surface of a sample at a chemical level opens a vast array of applications, from academic

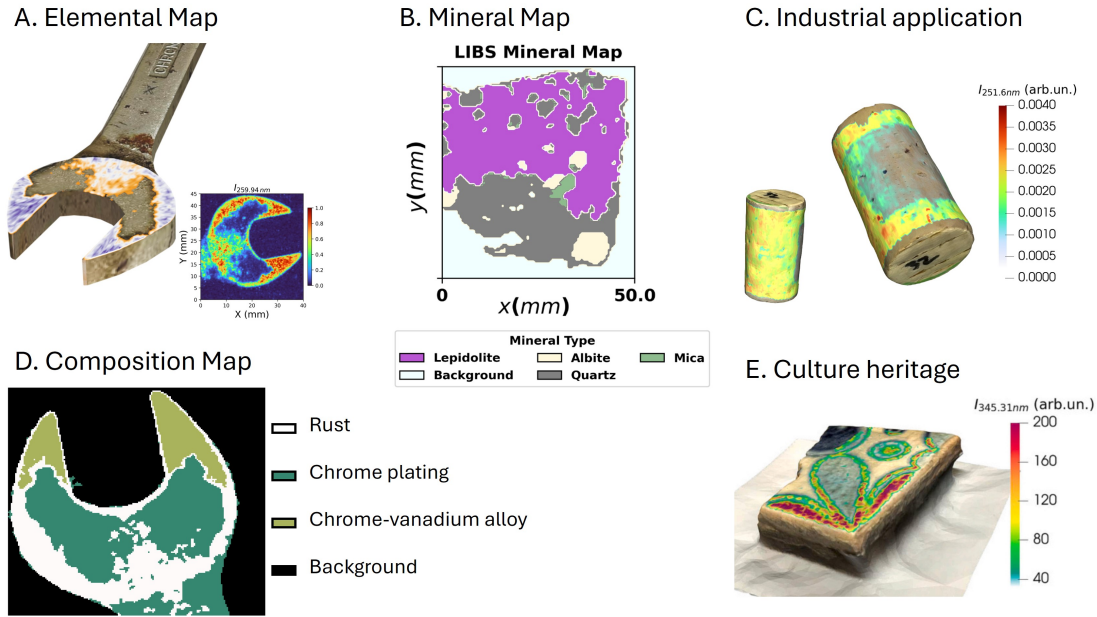


Figure 2.6: Some examples of the use of spectral imaging and LIBS technique to analyze samples. A. Distribution of Iron (II) (259.94 nm) at the surface of a wrench; B. Mineral Map characterization; C. Industrial application; D. Elemental distribution map; and E. Culture heritage application [3].

and laboratory environments to industrial settings (Figure 2.6 B and E). Indeed, in the last decade, LIBS-based imaging gained prominence in various research fields spanning diverse topics such as geological sciences (e.g. providing insights into the composition of minerals and rocks [57, 58]), medical and biological sciences (e.g. assisting in tissue analysis and diagnostics [59]), industrial applications (e.g. detecting contaminants during raw material recycling or monitoring the quality of products [60]), and even cultural heritage research (e.g. mapping the elemental composition of artworks and artifacts, to gain insights into the materials and techniques utilized [3]).

Another trend that is worth mentioning is that the analysis of these large spectral imaging datasets has benefited from recent developments in the field of machine learning and artificial intelligence. These days, data-driven yet robust solutions are starting to appear in the most diverse scientific fields [15] with particular highlight to the work of our team on the topic of mineral type classification using a multitude of unsupervised architectures [61].

2.2. Integration with 3D models

As seen in the previous section, the typical result from a spectral imaging dataset is a 2D image of a sample surface, containing no information regarding the surface shape or even the object itself. For this project, we set to tackle these limitations, exploring the use

of XR tools to enhance the user experience by integrating these images into 3D digital models of the samples. Thus, towards this purpose, the generation of three-dimensional models is also an important piece in this project.

There are multiple methods to scan a sample in order to produce a three-dimensional digital model, each offering different levels of precision and detail depending on the desired final model. Sophisticated systems, such as 3D laser scanning, can be utilized when higher resolution is required, particularly for small objects (e.g., below centimeter scale) where capturing intricate details is a priority [62]. For larger areas or when rapid data collection is necessary, LIDAR-based methods are ideal, offering efficient scanning over wide surfaces while maintaining an acceptable level of accuracy [63]. However, the most accessible and versatile solution is perhaps photogrammetry [64], a technique that requires only very basic setups and that can be performed with a standard smartphone or tablet.

Photogrammetry encompasses a wide range of methodologies for capturing and interpreting images to create accurate representations of physical objects and spaces[65]. In particular, using tailored algorithms and software solutions, it is possible to construct accurate 3D models of samples covering a wide range of size scales (from a few millimeters to many meters) in a non-invasive manner. To provide a practical example of the special relevance of photogrammetry, ancient monuments and artifacts are commonly scanned with this technique, allowing the preservation of cultural heritage and transmitting it to future generations by not only maintaining the current appearance of these structures, unaffected by the wear and tear of erosion, but also allowing for their digital preservation, which ensures that they remain accessible even as the physical versions deteriorate over time [66].

The working principle of this technique involves capturing multiple overlapping images or a video of an object/specific area from different angles (Figure 2.7 A) and stitching them together to create an accurate digital 3D model using reconstruction software [64, 67]. As illustrated in Figure 2.7 B, the model faithfully presents both the geometry and appearance of the real sample using well-known and widely disseminated software solutions such as the open-source software Polycam [68]. Notice that the intricate details of the object surface have been captured with remarkable precision to the millimeter range, showcasing the capability of the photogrammetry process. Besides, one of the major advantages of photogrammetry for these applications is that the reconstruction software also constructs

realistic textures to the model, enhancing its visual fidelity which may be crucial for XR applications.

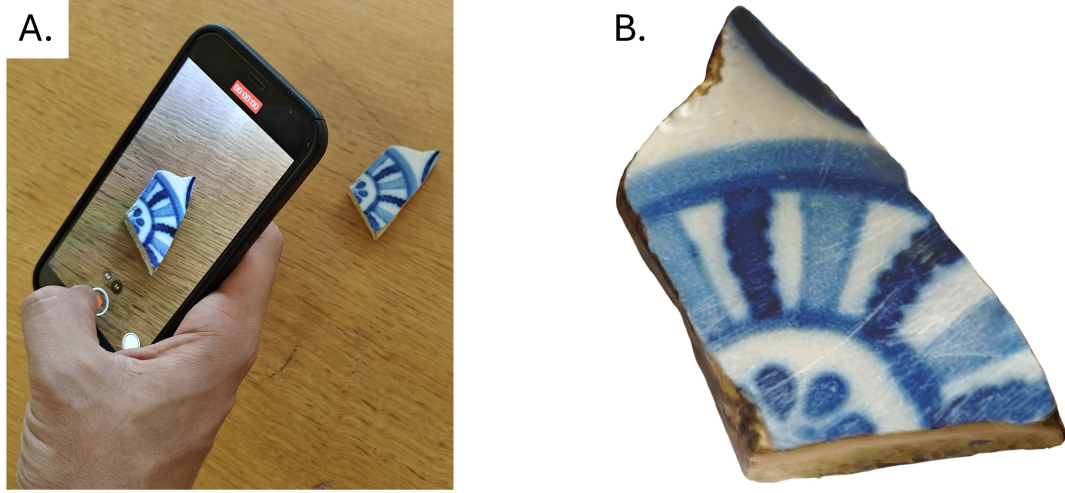


Figure 2.7: A. Typical method to photograph the 3D model. B. Tile sample reconstructions accomplished with its texture.

2.2.1 Fusing with Spectral Images via Mesh Matching

As the goal is to overlay spectral imaging onto 3D models, it is then crucial to align both models. To achieve this, we need a Mesh Matching Algorithm, i.e., an algorithm that aligns and overlays the spectral imaging data onto the 3D model at the correct location, ensuring that the spectral information is precisely mapped onto the region where the data was originally collected.

Following the results of a recent approach by our team at INESC TEC [3], a possible solution is to utilize the Kabsch-Umeyama Algorithm [69], which is designed to find the optimal transformation parameters for translation, rotation, and scaling ($\vec{t}$, $\mathbf{R}$, s) between two sets of points $\vec{p}_i$ and $\vec{q}_i$ by minimizing the mean squared error as:

$$\epsilon(\vec{t}, \mathbf{R}, s) = \frac{1}{n} \sum_{i=1}^n \left\| \vec{q}_i - (s\mathbf{R}\vec{p}_i + \vec{t}) \right\|^2 \quad (2.1)$$

In our context, the sets of points $\vec{p}_i$ and $\vec{q}_i$ correspond to user-selected points in the 3D model and in the spectral imaging data, where a set of matching points is selected in each.

Mathematically, these selected points, corresponding to the same spatial region in both the 3D model and the 2D image, can be represented by two matrices (Equation 2.2) that

contain the set of points intended to be aligned:

$$\mathbf{P} = \begin{pmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ \vdots & \vdots & \vdots \\ x_m & y_m & z_m \end{pmatrix} \quad \text{and} \quad \mathbf{Q} = \begin{pmatrix} i_1 & j_1 & k_1 \\ i_2 & j_2 & k_2 \\ \vdots & \vdots & \vdots \\ i_m & j_m & k_m \end{pmatrix} \quad (2.2)$$

To solve the minimization problem, we may start by computing the cross-covariance matrix, Σ_{PQ} , for the point patterns $\mathbf{P}$ and $\mathbf{Q}$ as

$$\Sigma_{PQ} = \frac{1}{n} \sum_{i=1}^n (\vec{q}_i - \vec{\mu}_q)^T (\vec{p}_i - \vec{\mu}_p) \quad (2.3)$$

where $\vec{p}_l = (x_l, y_l, z_l)$ and $\vec{q}_l = (i_l, j_l, k_l)$ correspond to the same spatial points in the distinct meshes, and $\vec{\mu}_B$, $B \in \{P, Q\}$, corresponds to the position of the centroid, defined as:

$$\vec{\mu}_B = \frac{1}{n} \sum_{l=1}^n \vec{b}_l \quad (2.4)$$

The next step is to decompose the matrix Σ_{PQ} using Singular Value Decomposition (SVD), i.e., $\Sigma_{PQ} = \mathbf{U}\mathbf{D}\mathbf{V}^T$ ($\mathbf{D} = \text{diag}(d_i)$, $d_1 \geq d_2 \geq \dots \geq d_m \geq 0$) which according to ref. [69], leads to optimal transformation parameters that minimize the mean squared error given by:

$$\begin{aligned} \text{Rotation} : \mathbf{R} &= \mathbf{U}\mathbf{C}\mathbf{V}^T \\ \text{Scaling} : s &= \frac{1}{\sigma_p^2} \text{tr}(\mathbf{D}\mathbf{C}) \\ \text{Translation} : \vec{t} &= \vec{\mu}_Q - s\mathbf{R}\vec{\mu}_P \end{aligned} \quad (2.5)$$

where σ_p^2 e σ_Q^2 correspond to the variances of matrices $\mathbf{P}$ and $\mathbf{Q}$, respectively, given by $\sigma_B^2 = \frac{1}{n} \sum_{l=1}^n (\vec{b}_l - \vec{\mu}_B)^2$ and:

$$\mathbf{C} = \begin{cases} \mathbf{I} & , \text{ if } \det(\mathbf{U})\det(\mathbf{V}) = 1, \\ \text{diag}(1, 1, \dots, 1, -1) & , \text{ if } \det(\mathbf{U})\det(\mathbf{V}) = -1. \end{cases} \quad (2.6)$$

The fact that the matrix $\mathbf{C}$ has the presented structure ensures that the rotation matrix $\mathbf{R}$ retains the correct orientation, even when the alignment involves a reflection. Note however that under this formulation the deployed algorithm is dependent on the order of the points that construct both matrices, i.e. point $\vec{p}_i$ corresponds to point $\vec{q}_i$. This condition can be relaxed by computing additional figures of merit as suggested in [3].

2.3. Workflow - From Data Acquisition to the Final Model

With the algorithm established, the next step is to select the appropriate software tools for generating the final 3D model and provide a visualization platform procedure. To accomplish this, we utilize the ParaView software [70]. ParaView is an open-source solution that offers a graphical user interface that enables researchers to interactively explore three-dimensional datasets. It is designed to scale up to large-scale data visualization through hardware acceleration and distributed computing techniques and particularly excels in handling large datasets, visualizing multidimensional data, and performing complex geometric transformations. In essence, ParaView streamlines visual data analysis by allowing users to apply filters to datasets and subsequent filter outputs. Additionally, ParaView supports Python scripting, enabling task automation and batch processing, which is crucial for our work.

Utilizing Paraview, the visualization workflow proceeds as three consecutive steps, described in the sections below.

2.3.1 Step 1: Create a VTK model for the spectral imaging dataset

The first step involves processing the data acquired from the LIBS system and generating the corresponding chemical maps in a format compatible with ParaView. ParaView is built on the Visualization Toolkit (VTK) [71], requiring a preferred format for input data, ensuring seamless integration with the software. Following the required preprocessing and the generation of 2D chemical maps (see Figure 2.8), a two-dimensional structured grid is created to store the generated matrix as `PointData`. These tasks are executed using Python and can be efficiently implemented by utilizing the *pyevtk* library, which handles VTK native formats.

2.3.2 Step 2: Create a 3D model of the sample

Secondly, for the same samples analyzed, a 3D model reconstruction is conducted using the photogrammetry technique. For the purpose of this work, a video of each sample was recorded using an iPhone 12 smartphone camera as it has sufficient quality, and the reconstruction was performed with the open-source Polycam software, resulting in a realistic three-dimensional model of the sample, including its respective texture. The generated model is then exported in the GLTF format and converted in the computer into the OBJ format, a more widely supported standard in visualization software. The texture

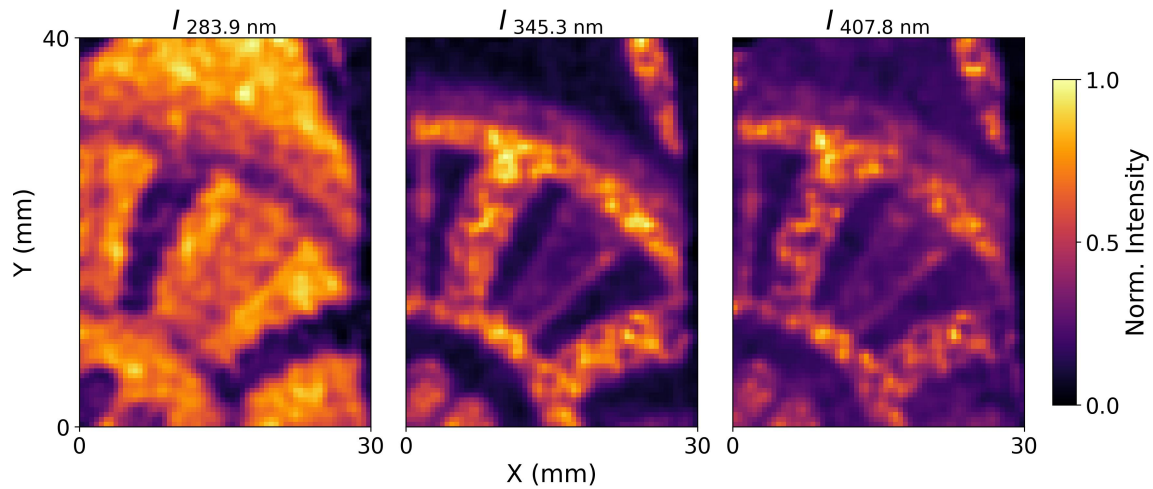


Figure 2.8: Spectral images generated for a tile sample (for further information see Section 4.1.1) showing the maps generated for emission lines at 283.9 nm (Sn), 345.3 nm (Co), and 407.8 nm (Pb).

was extracted to PNG to be later applied in ParaView. A result of this process can be visualized in Figure 2.7 (B).

2.3.3 Step 3: Align both models and fuse them into a single 3D model

The final step involves aligning the 3D model with the spectral images. This alignment can be carried out directly in the ParaView software, in particular by exploiting the ability to execute Python scripts for task automation (see details in Appendix A.1).

To accurately align the spectral images with the 3D model, reference markers were first defined in both datasets. Any given number of points can be selected on each sample using the point selection tool of Paraview, as long as the same number of corresponding points is chosen in both datasets, based on similar features or characteristics.

Subsequently, a Python script is run in the ParaView shell to align the reference markers via the mesh matching algorithm previously discussed. It is important to note that the developed algorithm does not require the points to be selected in a specific order, as it automatically permutes all possible point pairs and selects the configuration that minimizes the distances between corresponding points between the VTK file and the 3D model. Finally, the transformed two-dimensional chemical map is mapped onto the three-dimensional model, creating an interactive visualization environment within the Paraview software. Typical workflow and results of the procedure are illustrated in Figure 2.9.

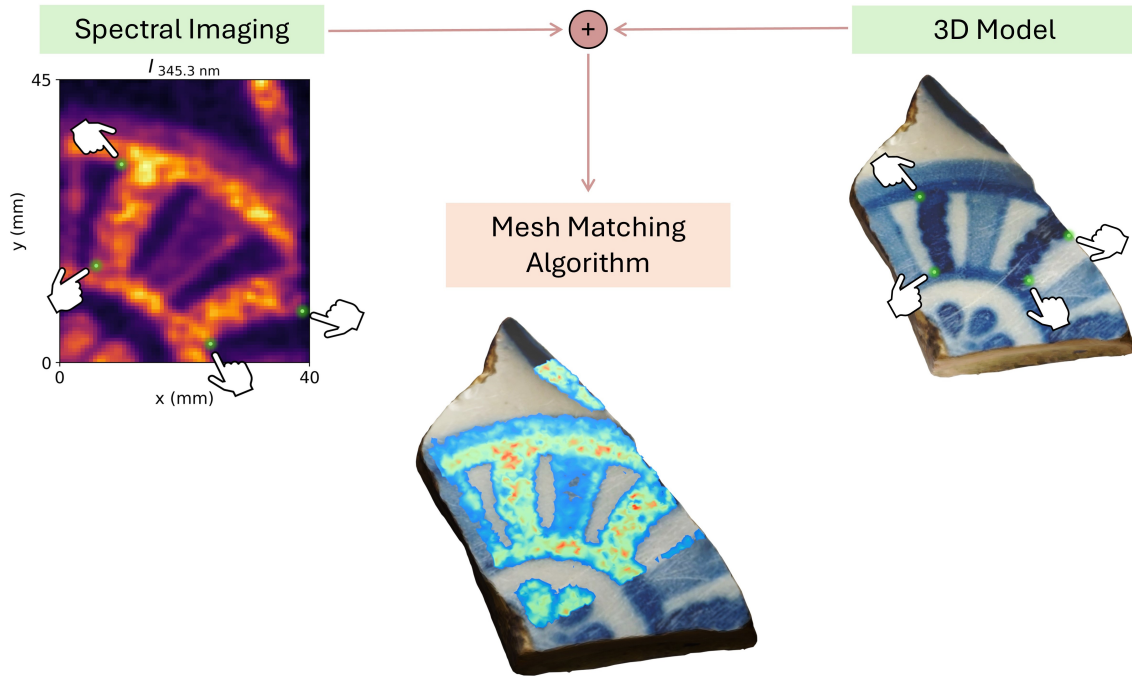


Figure 2.9: Illustrative procedure and results of the alignment between the 3D model and the spectral imaging.

2.4. Concluding Remarks

In this chapter, we introduced the foundational concepts necessary for understanding Spectral Imaging, with a particular focus on one spectroscopy technique, Laser-Induced Breakdown Spectroscopy. Additionally, we explored the process of creating 3D models through photogrammetry and discussed the algorithms involved in aligning these models with spectral imaging data. Overall, the qualitative analysis in LIBS proves to be a powerful tool for determining and visualizing the elemental composition of a sample, whereas its integration with 3D models enhances the visualization and contextual understanding of the spectral information, benefiting from information such as volume and texture.

Building on these foundations, our work will involve transferring these 3D models into the realm of Extended Reality, offering a pathway to a new data analysis environment, providing contextual interpretation along with unique interaction capabilities [30].

3. Extended Reality: Tools and Methods

As discussed in the introduction chapter, Extended Reality encompasses various types of technologies and devices that try to meet the specific needs of each application. In this chapter, we explore this field providing a contextual overview of the most relevant devices and recent trends, highlighting their key features, capabilities, and the specific contexts in which they are applied. Then, the focus shifts to the HoloLens 2, the central device used in this project, detailing its functionalities, specifications, operation, and applications. Finally, we describe the methodology utilized to develop tailored software solutions for this device, focusing on the Unity engine and the Mixed Reality Toolkit Package which will be fundamental later on.

3.1. Mapping XR Devices and capabilities

In the first section of this chapter we explore different XR solutions, ranging from hand-held devices and Heads-Up Displays (HUDs) to Head-Mounted Displays (HMDs) [72–74], highlighting their features, use cases, and the unique experiences they provide. In particular, we aim to highlight the advantages of our final choice in comparison with the others, as well as discuss its major features in order to exploit them in a convenient manner.

3.1.1 Handheld Devices

These days, handheld devices are perhaps the most common, versatile, and accessible form of XR. In generic terms, we call a handheld device any portable system, such as a smartphone or a tablet, that merges high-resolution digital images with real-world surroundings. For this, it utilizes internal cameras and processing capabilities, displaying the result on its own screen and transforming any space into an interactive scenario. These devices are particularly prominent in AR applications, with notable examples in gaming and shopping experience. An example is the popular game Pokémon GO, which uses AR to blend digital characters with the real world, allowing players to interact with virtual Pokémon as if they were present in their physical environment. AR is also used as an assisting tool in the retail market to improve customer experience and ultimately boost sales, such as showcasing clothes and accessories with lifelike animations or providing a convenient way to try on new pairs of sunglasses.

While these devices offer remarkable advantages including portability, high-resolution displays, and ease of use, they also come with limitations. Battery life is a common concern, as extended use often necessitates frequent recharging or reliance on external power sources. Additionally, these devices generally provide a lower level of immersion compared to other XR technologies, as they are constrained by their screen-based interfaces rather than offering a fully immersive experience.

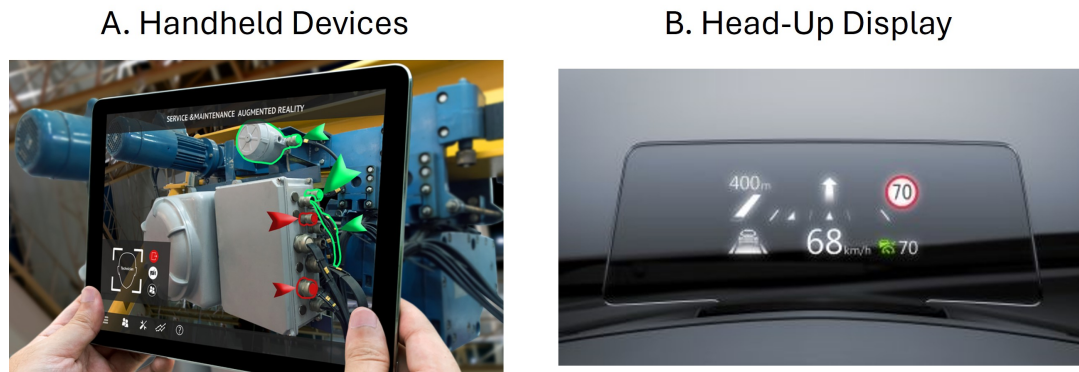


Figure 3.1: Examples of A. Handheld Devices used for industrial purposes, and B. Head-Up Displays used to assist in driving.

3.1.2 Heads-Up Displays

Following a close line of thought to handheld devices, HUDs are technological solutions designed to project digital information onto a transparent screen, allowing users to view data without losing awareness of the external environment or shifting their gaze from their usual viewpoints. This technology is frequently used in aviation and automotive industries [32, 73], where critical data are projected directly onto the windshield or a dedicated display panel.

The most common application appears in the automotive industry, where HUDs can display information such as speed, navigation instructions, speed limits, upcoming turns, and warning alerts directly without requiring the user to look away from their primary focus. Another critical utilization appears in aviation, where information such as altitude, air-speed, and navigation instructions provides pilots with essential information that can be challenging to access during complex maneuvers or adverse weather conditions, where maintaining situational awareness is crucial.

The major advantage of this solution is that it enhances situational awareness and safety by integrating essential information in real-time directly into the user's line of sight [75]. However, studies also indicate that under high workload conditions, the risk of inattentional

blindness increases [76]. Besides, these devices are designed for a fixed purpose, losing a significant amount of versatility and interactivity with the data and the full experience of AR.

3.1.3 Head-Mounted Displays

The last category we want to highlight are HMDs, which are wearable devices that allow for great mobility and provide the most capable user-centric interactive environments as they are equipped with advanced technology that enables a higher degree of presence and graphical quality when compared to smartphones and tablets [77].

C. Head-Mounted Display



Figure 3.2: Illustration of C. Microsoft's HoloLens 2 MR device (left) and Meta's Quest 3 VR device (right).

Nevertheless, depending on their specific applications and target market, features vary a lot between distinct models. For example, some headsets are designed to fully immerse users in a completely virtual environment, known as VR headsets (see Figure 3.2). These headsets typically feature high-resolution displays, wide fields of view, and built-in motion tracking, all of which work together to create a strong sense of presence in a 3D space. The most common models are Oculus Quest 2 and PlayStation VR2, which are primarily used for gaming, simulations, and virtual tours, offering a fully immersive experience that isolates the user from the real world [23].

On the other hand, there are AR and MR headsets that overlay digital information onto the physical world. These can be further subdivided into two categories: Optical See-Through HMDs, which allow users to see the real world directly through a semi-transparent screen, as seen in the Microsoft HoloLens 2 (see Figure 3.2); and Video See-Through HMDs, which use cameras to capture the real world and display it on head-mounted screens, as exemplified by the Apple Vision Pro. This category of headsets is ideal for applications

that require high levels of interaction between digital and physical elements, such as advanced training simulations and complex design tasks, and are used in various fields, as mentioned in the next section 3.2.1, including industrial training, remote collaboration, and interactive design.

Yet, HMDs still face significant technological challenges that need to be addressed to enhance user experience. One major issue is latency - delays between the user's movements and the update of digital images, which can cause discomfort or even nausea. This problem has been highlighted in devices like the Apple Vision Pro, where the process of recording the environment and then displaying it can introduce noticeable lag. Another critical area for improvement is hand tracking; enhancing the accuracy and responsiveness of motion tracking would allow for more intuitive interactions and open up possibilities for new movement functionalities. From the user's perspective, improving screen resolution and expanding the field of view is essential for creating more immersive and realistic experiences, whereas reducing the weight and size of these devices is crucial to making them more comfortable for prolonged use, minimizing physical strain on users.

3.1.4 Comparative Analysis

Each of these XR devices offers distinct advantages depending on the application and user needs and therefore it is hard to declare one technology superior to another.

For instance, if the goal is to achieve a highly immersive experience, HMDs are likely the most suitable choice due to their advanced interactivity options and ability to create a fully immersive environment. On the other hand, if the focus is on accessibility and ease of use in everyday applications such as gaming, education, or content creation, handheld devices may be the better option. Their portability and user-friendly interfaces make them ideal for a wide range of users. For situations where maintaining focus on a task while receiving supplemental information is crucial, HUDs are the preferred solution.

The table below provides a summary of the key characteristics of each technology, highlighting their differences in immersiveness, mobility, interactivity, field of view, and cost.

Based on the comparative analysis of XR devices, HMDs emerge as the most suitable choice for this project. In our specific case, having the ability to manipulate 3D models in a real-world environment while maintaining a high degree of interactivity is essential for the tasks we aim to accomplish.

Feature	Handheld Devices	HMDs	HUDs
Immersiveness	Low	High	Medium
Portability	High	High	Low
Interactivity	Medium	High	Low
Field of View	Limited	Wide	Limited
Cost	Low	High	Medium

Table 3.1: Comparison of display technologies across different characteristics.

Furthermore, the ability to observe the physical environment directly, while interacting with digital elements, is a key requirement, since it avoids low latency problems normally associated with video See-Through HMDs.

3.2. HoloLens 2 Device: features and specifications

Nowadays, several companies have been at the forefront of the development of XR technologies, including Microsoft, HTC Corporation, XREAL, Meta, and Magic Leap, with their respective products, such as the HoloLens 2 [78], HTC Vive Pro 2 [79], XREAL Air [80], Meta Quest Pro [81] and Magic Leap 2 [82]. This work will focus specifically on the HoloLens 2 device, an ergonomic and wireless device designed for both AR and MR technology.

The HoloLens 2 is an AR and MR-based Head Mounted Display (HMD), i.e., a wearable and autonomous device that offers an intuitive and immersive interface, integrates seamlessly virtual data into the user's field of vision, allowing him to perceive the real world while enjoying a comfortable and high-quality Mixed Reality experience. It operates on the Windows Holographic Operating System, providing a robust environment for developing and deploying MR applications, being equipped with advanced hardware and software features that contribute to its immersive capabilities.

First focusing on the display technology, it uses a sophisticated combination of optical waveguides and laser diodes as light projectors (RGB) to display holograms on top of the real world. The light is pulsed (one pulse per pixel) and steered via Micro-Electro-Mechanical Systems (MEMS) mirrors, controlling the direction of the laser beams with precision entering the waveguides (Figure 3.3). The optical waveguides, embedded within the visor lenses, are physical structures that utilize the principle of total internal reflection to guide electromagnetic waves through the material [83], and allow precise location of the images on the user field of vision [84, 85]. The perfect synchronization and precise control

of this optical see-through holographic system allow for the formation of high-quality, full-color holograms, resulting in a holographic resolution of 2k 3:2 light engines and providing a comfortable viewing experience [86].

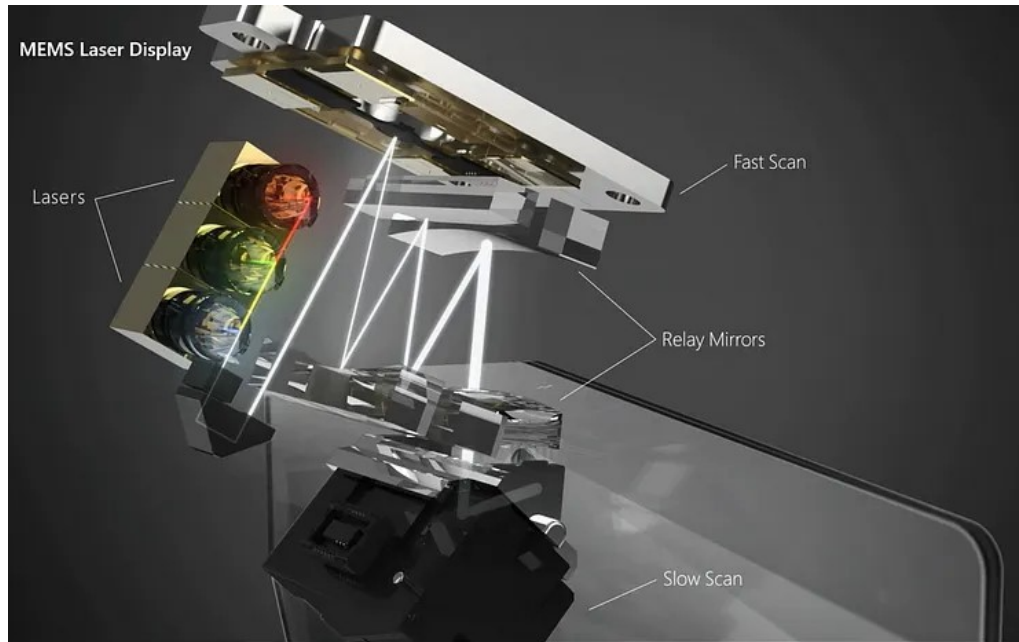


Figure 3.3: Diagram of the MEMs laser display in HoloLens 2, showing the path of laser beams through fast and slow scanning mirrors, redirected by relay mirrors to create the visual projection. (Adapted from [78])

To add MR capabilities and interact with the surroundings, the HoloLens 2 is also equipped with a sophisticated array of cameras and sensors that contribute to its precise tracking and immersive capabilities. The device includes:

- **4 visible light Cameras** located at the front corners track the user's head movement for the purpose of ensure that the holograms stay accurately positioned in the user's field of view as they move their head;
- **2 Infrared (IR) cameras** embedded within the device monitor the position and movement of the eyes in real-time, enabling gaze-based interaction and enhancing the precision of hologram placement based on where the user is looking;
- **Depth Sensor** map the environment in 3D, playing a vital role in recognizing surfaces and obstacles within the user surroundings;
- **Inertial Measurement Unit (IMU)**, composed of an accelerometer, gyroscope, and magnetometer, is used to track the orientation and movement of the device in space, measuring 3 degrees of freedom for position (x, y, z) and 3 degrees of freedom for orientation (roll, pitch, yaw); and

- **8MP Camera** positioned on the front of the device captures high-resolution still images and records 1080p video at 30 frames per second.

The layout of these components is schematized in Figure 3.4.

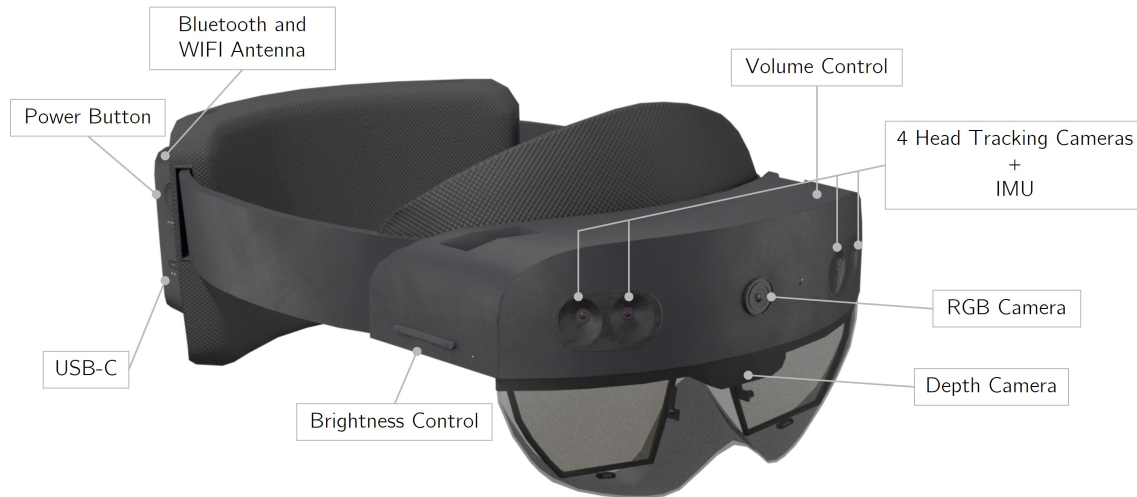


Figure 3.4: The basic hardware of Microsoft HoloLens 2.

Additionally, the device has spatial sound technology, which uses built-in speakers to provide 3D spatial audio, further immersing the user in the Mixed Reality experience. These set of components work together to deliver a smooth and responsive user experience, enabling complex interactions and real-time processing. Therefore, the device allows for eye-based rendering with the particularity to:

- Monitor user movements and track hand gestures for precise control and natural interaction with holograms, including touch, grasp, and manipulation;
- Recognize real-world surfaces and space to seamlessly add and adjust holograms in real-time;
- Understand voice commands to facilitate hands-free operation or to quickly navigate on HoloLens 2;
- Utilize eye tracking that continuously monitors pupil position through advanced sensors; and
- Provide a natural experience by allowing the user to observe their surroundings without any disruption, seamlessly integrating virtual holograms into the real-world environment.

Finally, HoloLens 2 also includes enhanced connectivity features, with WiFi and Bluetooth for fast and stable wireless communication, allowing seamless streaming of data or interaction with cloud-based services. To connect to physical devices it also features a USB Type-C port for charging and data transfer, as well as physical buttons to control volume, brightness, and power.

3.2.1 Applications

To further understand the potential of this device we will now cover some AR and MR applications using HoloLens 2 with emphasis in the fields of education, engineering, and manufacturing for illustrative purposes.

First focusing on education, AR/MR technologies can significantly enhance the teaching and learning experience by allowing learners to visualize complex spatial relationships and abstract concepts that are often difficult to grasp through traditional methods. These technologies enable students to experience phenomena that are not possible in the real world, thus improving their learning curves and deepening their understanding of the subject matter [36–38]. In particular, it enables the creation and presentation of 3D models of objects that would be challenging or impossible to explore in reality due to their rarity, size, or complexity (e.g. complex molecules or large machinery, see Figure 3.5). Adding labels and descriptive overlays also allows better identification of each component, helping students better understand core concepts through spatial visualization.



Figure 3.5: Examples of educational applications: A. Studying a holographic model of a human spine for detailed analysis. B. Students and educators interacting with holograms to study molecules like H_2O and CH_4 . (Adapted from [78])

Looking at the field of engineering and manufacturing, AR and MR technologies are commonly used to enable collaborative work among engineers, streamline complex assembly processes, and provide dynamic remote assistance and guided workflows (Figure 3.6).

An interesting application of major impact is the real-time monitorization of safety conditions in human-robot collaboration [41, 42], where an AR user interface monitors and secures a minimum protective distance between a robot and an operator in the industrial manufacturing field utilizing the depth sensor and providing instant feedback to the user's field of vision. Another practical example can be seen in the case of Airbus, which uses Microsoft HoloLens 2 to enhance the aircraft production process and reduce errors [87]. In particular, the headsets are regularly utilized to assist workers in complex tasks such as wiring harness installation and cabin inspection, allowing them to access digital instructions, schematics, and checklists while keeping their hands free.

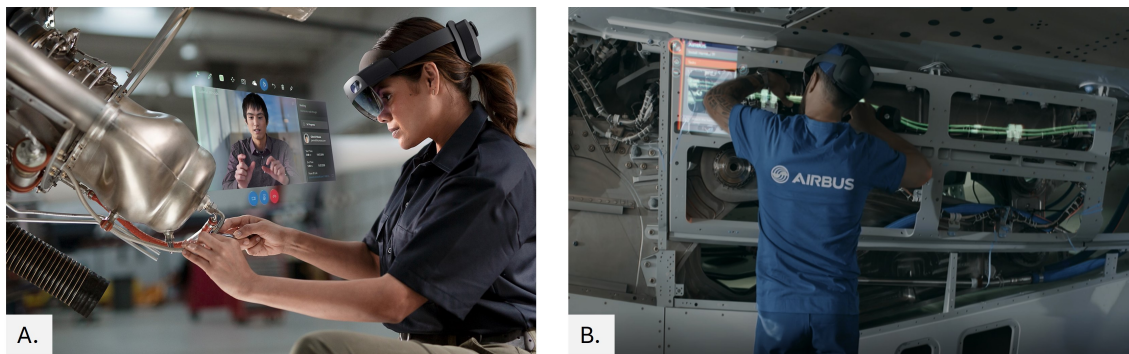


Figure 3.6: Applications in engineering and manufacturing: A. Example of remote assistance and guides, and B. Airbus worker using real-time access to information and instructions while their hands are occupied with assembly tasks.

However, HoloLens 2 also features some drawbacks that hinder the broader introduction of this technology in real-world applications. Major obstacles include the high cost (above 3k€), the connection requirements required for remote collaboration [88], and worker fatigue (e.g. a reduction in blink rate in workers [89], which can result in eye fatigue and dry-eye symptoms).

3.2.2 Development of Software Solutions for HoloLens 2

To develop tailored software solutions for this device, we opted to use the Unity Real-Time Development Platform and the Mixed Reality Toolkit Package. Unity is a versatile game engine commonly used to create 3D and 2D interactive content. Unity excels in real-time rendering, which together with its cross-platform capabilities makes it a natural choice for a more versatile approach [90, 91]. To better explore AR and MR capabilities, the Mixed Reality Toolkit (MRKT) package for Unity was also utilized for the purpose of this project. The MRKT adds a unique collection of components and advanced functionalities

such as spatial mapping, hand tracking, and eye tracking, which are essential for creating immersive and interactive experiences.

Development in Unity allows for real-time updates and testing, facilitating iterative improvements and ensuring that the final application is both functional and user-friendly. Moreover, Unity's compatibility with the HoloLens 2 platform further solidified its selection as the development environment of choice. Once the project development was complete, the next step was the deployment process, which involved the transference of the project from the Unity engine to the HoloLens 2. This was done using Visual Studio 2019, a stable version compatible with the MR device.

During both project development and deployment, a set of specific configurations is necessary to ensure it functions as intended on the target device. A more detailed step-by-step procedure for this configuration can be found in Appendix B.

3.3. Concluding Remarks

In this chapter, we described various categories of XR devices, covering their advantages and disadvantages, concluding the Head-Mounted display is the most suitable for our project objectives. We then introduced the HoloLens 2 device, discussing its key features and functionalities, and providing a brief overview of its capabilities by presenting some of the most relevant applications across different fields. We also outlined our approach to developing and deploying applications for the HoloLens 2 using Unity and Visual Studio and that supports the original work presented in the next two chapters.

4. Bridging Spectral Imaging with Augmented Reality

Having addressed the topics of spectral imaging and Extended Reality in previous chapters, we can now proceed to the core purpose of this thesis: developing XR solutions to enable the visualization and analysis of spectral data in an immersive environment, overlaid on its 3D model. In the next two chapters, we will present two distinct approaches - one being an AR and the second one being an MR solution - with very unique characteristics and potential for future applications well beyond the timeframe of this work.

This chapter aims to describe the development of an AR solution for spectral imaging datasets. Without entering cumbersome details, it covers the methodology and the most relevant aspects of the development and deployment of a user-friendly interface tailored for AR functionalities. We then analyze the potential of the solution, highlighting the Spectral Data Analysis Interface and the QR Code Integration for Dynamic Data Display, showcasing the potential of spectral imaging and Extended Reality combination. In view of these, we finally provide a critical discussion mentioning possible application scenarios and impact for future explorations.

4.1. Method

In order to develop an AR solution to integrate spectral imaging datasets onto 3D digital models, we implemented a full-stack methodology and data processing pipeline encompassing both experimental and computational procedures. In generic terms, the solution consists of a three-step process as illustrated in Figure 4.1 and that will be further detailed in the subsequent sections. The first step focuses on **data acquisition & analysis** and comprises a processing pipeline designed for obtaining and preprocessing the spectral imaging dataset, constructing spectral maps, and acquiring the 3D model of the object. The second step concerns **asset management** and involves the integration of spectral imaging with the 3D models via mesh alignment, resulting in the data input necessary to be fed to the AR environment. Finally, the third step covers the **Development and deployment a Unity software solution** as a user-friendly interface for effectively exploring the acquired spectral data.

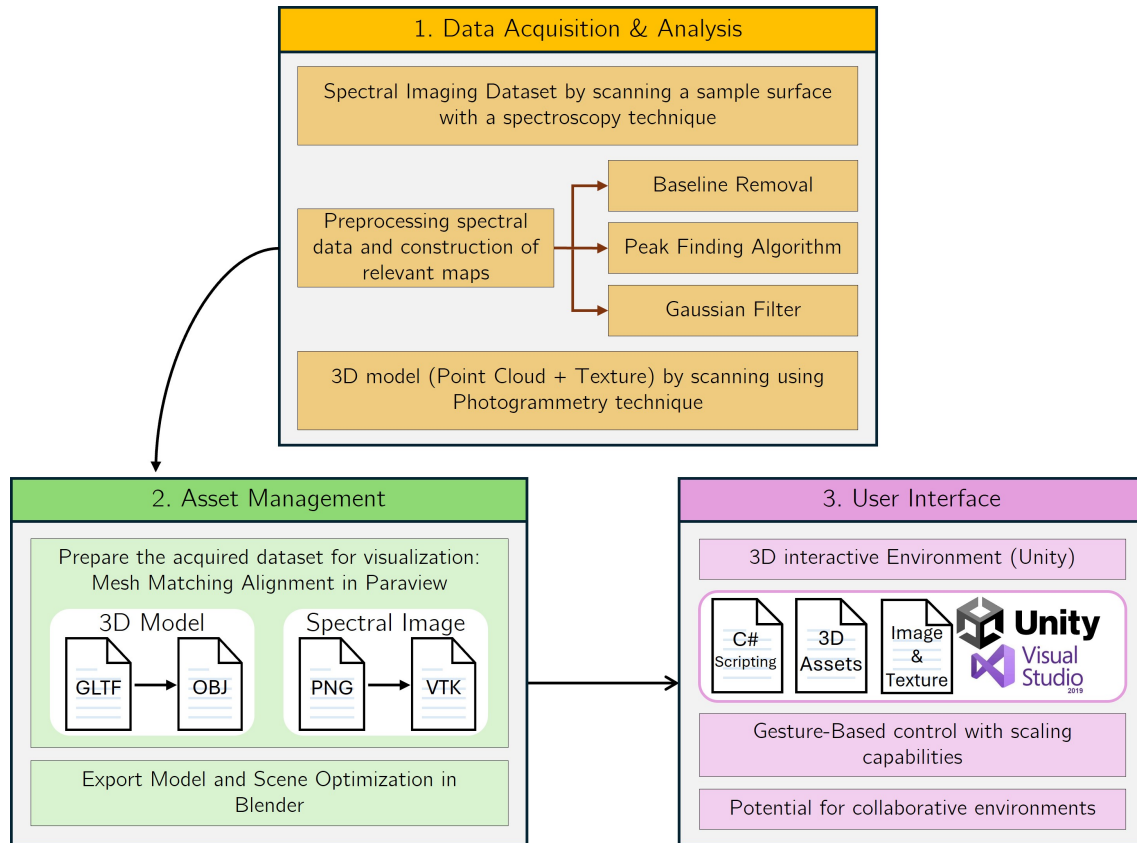


Figure 4.1: Schematic of the described methodology to deploy an interactive visualization tool for HoloLens 2 device, broken into the three steps referred.

4.1.1 Data Acquisition & Analysis

The first step in the pipeline depicted in Figure 4.1 involves two primary tasks: i) acquiring the spectral imaging dataset using LIBS and turning them into 2D spectral images, and ii) constructing the 3D model of the samples through photogrammetry.

For the spectral data collection, we utilized the LIBS prototype previously described in Chapter 2, operating at a frequency of 20 Hz with a pulse energy of 51 mJ. The acquired dataset was then subjected to baseline removal as part of the preprocessing steps (also discussed in Chapter 2). Each spectral map is then constructed by integrating the data in the wavelength dimension around the selected spectral line and subsequently applying a spatial Gaussian filter in the spatial transverse directions to refine the spatial resolution. These steps are vital for enhancing the accuracy and clarity of the spectral information before its integration with the 3D models. All these processing steps are carried out through Python scripts and streamlined user-centric actions. The decision to perform these steps in advance (and not directly into the software solution) was driven by efficiency considerations and memory limitations. Indeed, the generated spectral imaging datasets typically

have large memory footprints (often in the order of gigabytes), demanding significant processing power to ensure smooth and effective operation which is incompatible with the Hololens processing power.

For the photogrammetry process, the 3D reconstruction of the samples was generated by capturing videos using a smartphone, which was then loaded into Polycam software to create a realistic three-dimensional model of the sample, complete with the respective texture.

This entire procedure was applied to three different samples in order to better showcase the capabilities of the technology. For each, the spectral analysis focused on identifying elements that could effectively characterize them, particularly those with spatial information that would be of interest when visualized in spectral imaging, ensuring that the subsequent analysis would provide valuable insights.

Sample 1: Tile fragment

The first sample analyzed was a fragment of a traditional Portuguese tile, a sample of special relevance as a cultural heritage artifact. Indeed, the study of the spatial distribution of chemical elements on such samples (as depicted in Figure 2.8) underscores the capability of LIBS to identify and analyze heritage artifacts, thus holding potential for the study and preservation of cultural heritage artifacts. In such tiles, the distribution of cobalt (Co) is particularly noteworthy as part of the paint used in the tile associated with the blue pigmentation [92]. The presence of lead (Pb) is also common, as it was historically used to help fuse the glaze and pigment during firing, providing both durability and a glossy finish to the tile. These two elements are more intensely concentrated in the blue regions of the tile.

Interestingly, it is also possible to identify the complementary aspect of the blue paint by looking for the chemical element tin (Sn). This is because tin, in the form of tin oxide (SnO_2), is also commonly used as an opacifier in the glaze to create the white background, which enhances the vibrancy and contrasts with the blue cobalt pigment.

Sample 2: Oxidized double open-end wrench

A second sample consisted of a double open-end wrench, featuring a spatial distribution of oxidation. The idea is to highlight the capabilities of the technology for utilization closer to industrial applications, such as quality control and monitoring. For the case of the wrench

sample, it is detected the presence of a spatial distribution of Iron (Fe) (I) and (II) emission lines, as well as Vanadium (V), Chromium (Cr), Aluminum (Al), and Oxygen (O) (Figure 4.2). All of these are consistent with the surface oxidation observed on the sample. On one hand, the presence of iron, chromium, and vanadium is consistent with the chrome-vanadium steel composition. On the other hand, Al and O lines were detected with a higher intensity as they are part of the protective coating, revealing the less damaged part.

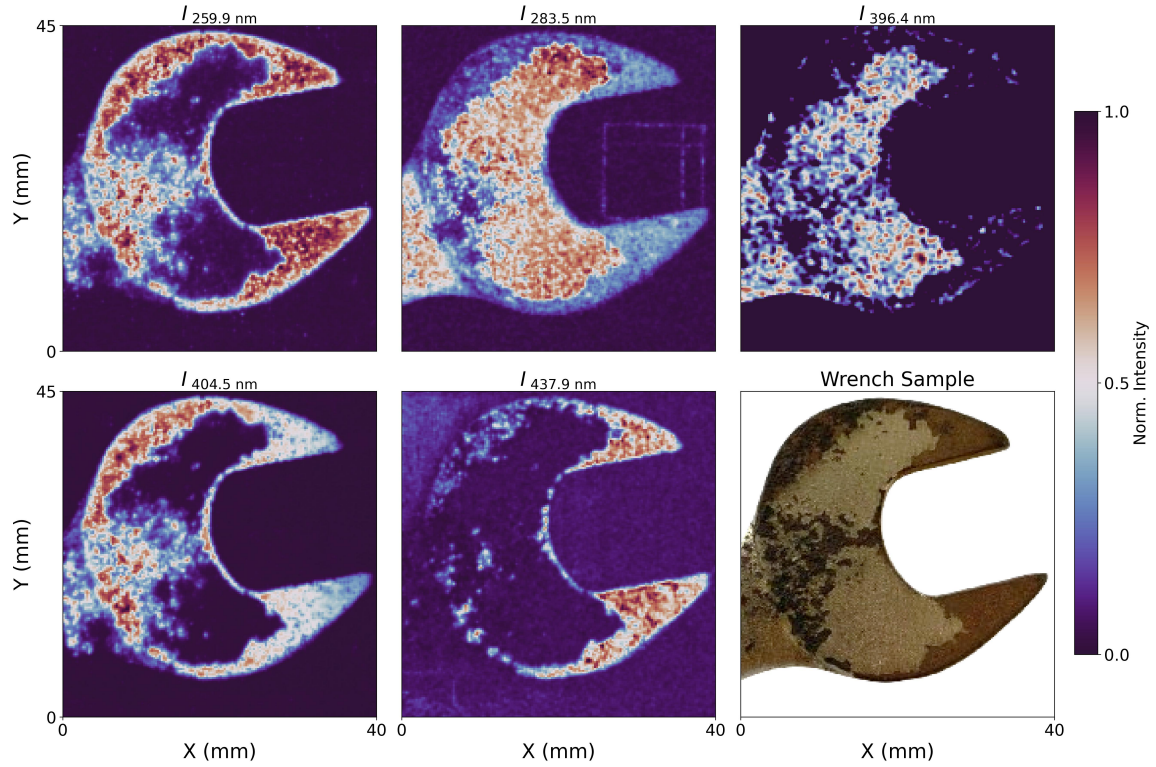


Figure 4.2: Spectral images of the wrench sample show emission lines at 259.9 nm, 283.5 nm, 396.4 nm, 404.5 nm, and 437.9 nm, corresponding to Fe II, Cr, Al, Fe I, and V, respectively, alongside the associated optical image.

Sample 3: Rock sample

The third and final sample analyzed was a rock with a mineralogical composition comprising albite, lepidolite, amblygonite, quartz, and mica, as detailed in Table 4.1. For this sample, we mapped the distribution of three key chemical elements: Aluminum (Al), Silicon (Si), and Potassium (K). These distributions are illustrated in Figure 4.3 and show the spatial intensity of the emission lines at 257.52 nm, 288.14 nm, and 693.87 nm corresponding to Al, Si, and K, respectively.

The spectral images reveal that each chemical element exhibits a distinct spatial distribution across the rock surface, which aligns with the expected localization of the associated

Mineral	Chemical Composition
Albite	$NaAlSi_3O_8$
Lepidolite	$KLi_2AlSi_4O_{10}F(OH)_2$
Amblygonite	$LiNaAl(PO_4)F(OH)$
Quartz	SiO_2
Mica	$KAl_2(AlSi_3O_{10})(OH)_2$

Table 4.1: Chemical composition of the minerals observed in the samples.

minerals within the sample. For instance, regions with higher concentrations of silicon could provide insights into the location of Quartz, as it is one of its primary components. Aluminum might correspond to areas rich in Albite, Lepidolite, or Mica, while potassium distributions could help localize Lepidolite and Mica. Using it is possible to deploy mineral classification tools with unsupervised clustering methods to more accurately classify the mineral regions in the sample [4], showcasing the potential of the technology for the mining industry sector.

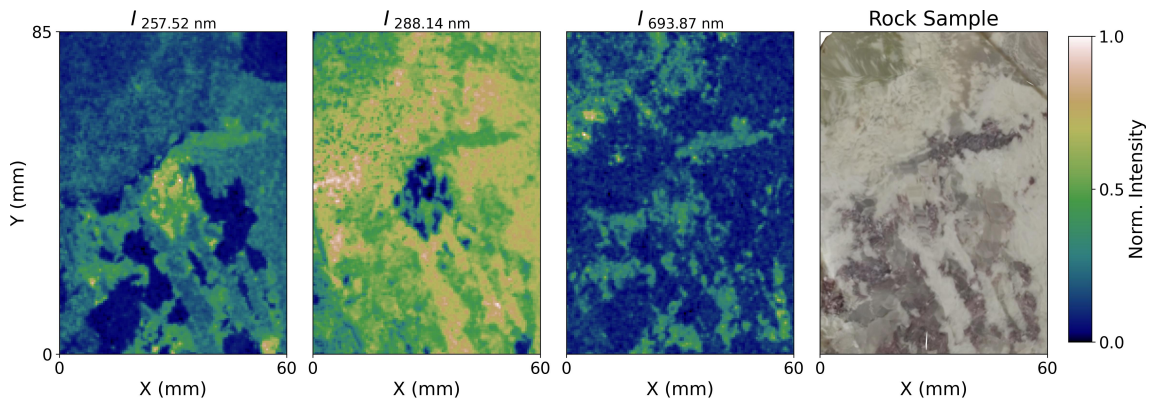


Figure 4.3: Spectral images of the rock sample show emission lines at 257.52 nm, 288.14 nm, and 693.87 nm, corresponding to the chemical elements Al, Si, and K, respectively, alongside the associated optical image.

4.1.2 Assets Managements

Asset management involves the processes required to manage, integrate, and prepare the acquired datasets for visualization. Building on top of the datasets obtained in the first step, this stage comprises the necessary tasks to merge the analyzed spectral dataset, presented as images, with the 3D digital model of the sample. This integration is achieved using a mesh matching algorithm previously presented in chapter 2.2, and executed semi-autonomously using the ParaView Software (v5.11.2), requiring minimal user intervention (specifically, the selection of specified points).

Once the spectral data has been accurately aligned with the 3D model, the final 3D model, now containing superimposed information layers, is exported from ParaView as GLTF files and then imported into Blender 4.0 [93]. Here, additional adjustments are applied to the scene for optimal visualization, such as fine-tuning the colorbar, brightness, and textures, before the model is integrated into the software solution. Since the VTK 2D maps require transparency to highlight the most relevant parts of the spectral image, it was necessary to add two lines of code to the GLTF file generated by ParaView within the material characterization block:

```
"alphaMode" : "BLEND", "doubleSided" : true
```

Figure 4.4 illustrates examples of the integration of spectral imaging data for each of the analyzed samples, showcasing how the spectral information is effectively mapped onto the 3D models.

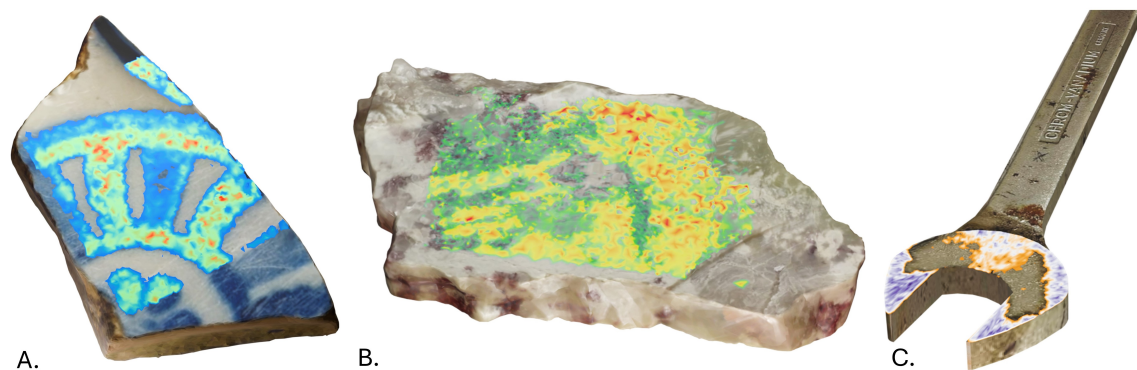


Figure 4.4: Illustrative results of three-dimensional interactive visualization models, representing (A.) Heritage applications (distribution of Cobalt on the surface of a Portuguese Tile, using the Cobalt line at 345.3nm), (B.) LIBS imaging dataset for a albite, lepidolite, amblygonite, quartz, and mica rock (distribution of Si emission line at 288.14nm), and (C.) LIBS data of an oxidized wrench (distribution of Fe (II) emission line at 259.9nm).

However, a challenge arises after exporting the final model from aligning the spectral imaging data in ParaView: the model becomes denser due to the inclusion of all points from the 3D model in each 2D VTK file, and the resulting model incorporates the entire 3D model with the VTK file overlaid, rather than accurately positioning the VTK file over the model sample. This issue makes the digital model much heavier than needed, which can lead to latency in loading and processing the models, as well as unnecessary memory usage. It is important to note that the more complex the model, the more challenging the process on the HoloLens 2 device.

To address this, a simplification of the model was performed via a Python script in the blender console, removing all faces that do not contain relevant information (transparent faces). This reduction decreases both the space occupied by the model and facilitates/reduces the processing time when loading them. The method used for this processing is straightforward: a Python script iterates through all faces of the model, removing fully transparent faces based on the alpha value of their textures (see Appendix A.2). For example, the wrench sample transitioned from a complex model of 109,568 faces to a simplified one with only 8,325 faces (Figure 4.5).

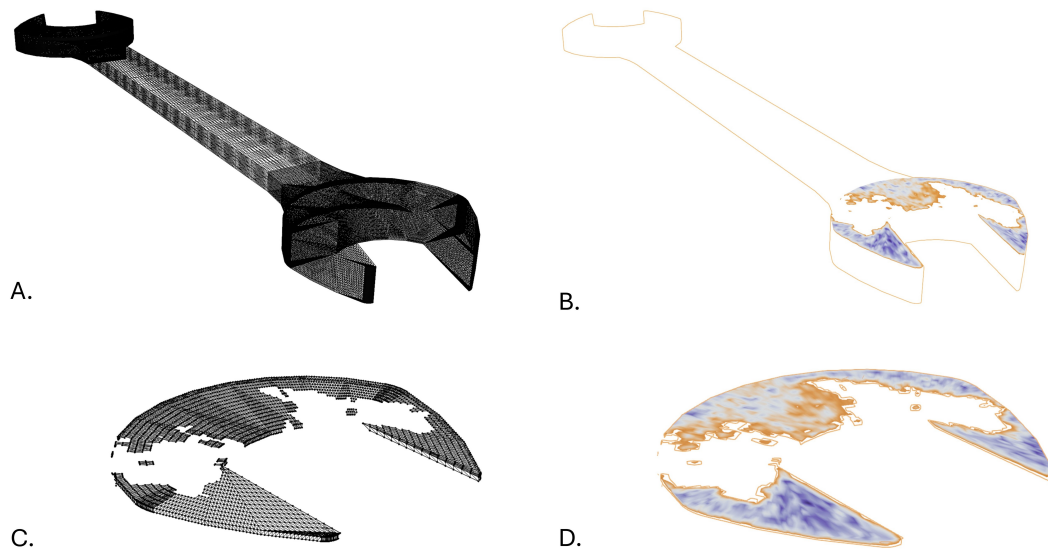


Figure 4.5: A. The complete model with 109568 faces (65484 vertices) and B. the corresponding 3D view. C. Simplified model with 8325 faces (5761 vertices) and D. the corresponding 3D view.

4.1.3 Development and deployment of a Unity software solution

In order to interact with the digital models in a meaningful manner for the context of spectral imaging, the simple upload of the generated models to a third-party 3D model visualizer on the Hololens 2 would be extremely limited. Indeed, a complete toolset requires not only the visualization of the model but also the interaction with the spectral data. This means for example to integrate a window to analyze the spectral signal, as well as additional solutions to shift between different spectral maps for the same sample and even putting multiple samples side-by-side for integrated analysis.

For that purpose, we opted to develop a tailored software solution, building a Unity project within a 3D Universal Windows Platform adapted to the Microsoft Hololens 2 headset. The resulting user interface consists of two complementary projects designed to address these requirements and provide a seamless experience for spectral imaging analysis.

4.1.3.1 Project 1: Spectral Data Analysis Interface

The first project developed in Unity is an interface designed for the immersive visualization and analysis of samples. The structure of the project within Unity is organized in a hierarchical manner, as shown in Figure 4.6, facilitating the efficient management of the scene and allowing for easy modifications and additions to the project as required. This hierarchy reflects the logical organization of objects and components within the scene, which is crucial for managing complex projects. At the top of the hierarchy, foundational elements such as the *MixedRealityToolkit* and *MixedRealityPlayspace* are positioned. The *MixedRealityToolkit* enables the integration of essential AR configurations and functionalities into the project, while the *MixedRealityPlayspace* primarily contains the main camera, providing the necessary perspective for AR interactions within the Unity environment. Below these foundational elements, the *MixedRealitySceneContent* node contains the specific models used in the project (i.e. loaded samples). The Canvas object includes all UI elements, ensuring that these components are correctly anchored and rendered in the 3D space. Additionally, the hierarchy includes the Menu prefab and *SampleCheckBox* components, which will be explored later in this section.

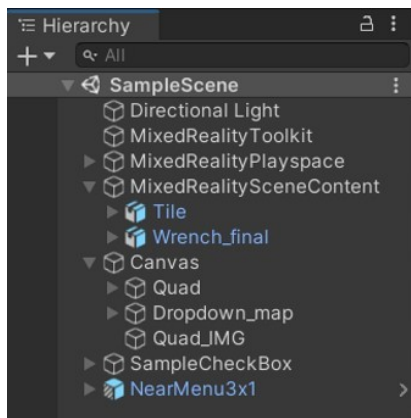


Figure 4.6: Unity project hierarchy.

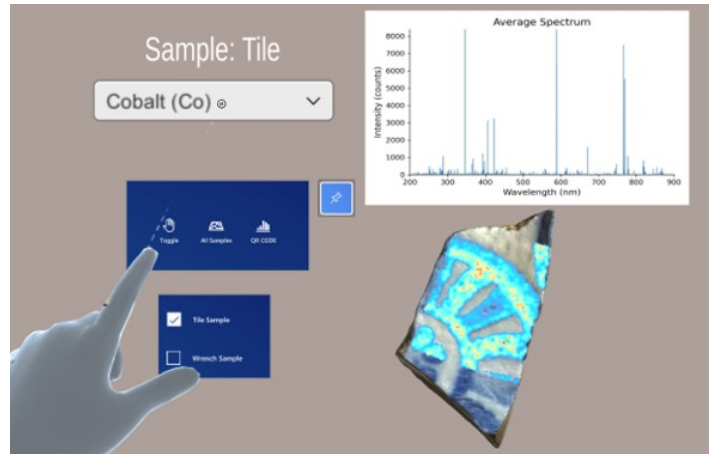


Figure 4.7: Scene view in the Unity editor.

In Figure 4.7 we present the designed interface, composed of a text box, a dropdown menu, a 2D graph, the sample itself, and a menu. Each one of these components has a particular function in the interface, with the information updated according to user interactions. The text box displays the sample name and a dropdown menu listing the relevant features for which spectral maps were previously generated (e.g. element lines for LIBS). The 2D graph exhibits the image generated in the first step containing the average spectroscopy signal for the sample, along with a vertical line indicating the chosen wavelength for the spectral image. Finally, in the center of the interface, the model of the sample

appears, displaying the selected spectral map seamlessly overlaid on the sample surface while preserving relevant object texture information. Collision properties and object manipulator functions were also added to the GameObjects to provide the elements with all the necessary gesture-based interactions.

The menu window can be utilized to access additional functions. Among these functions, the first button allows users to hide all elements of the interface except for the sample and menu to achieve an environment with fewer distractions. The second allows to access a list of samples, also enabling the simultaneous display of samples to facilitate comparative examination. Finally, a third function activates a QR code reading mode, redirecting the project to another scene (described in the next section) to allow users to move the sample to their desired location and load models directly from a remote server.

All of these buttons have the particularity of being voice-activated, allowing the user to have hands-free operation for other tasks. In the table 4.2, all the programmed voice commands are described:

Voice Command	Function
Toggle	Equivalent to pressing the "Toggle" button
All Samples	Equivalent to pressing the "All Samples" button to display the checkboxes with the existing samples
QR Code	Remote the interface to another scene
Pin	To pin the menu in place

Table 4.2: Table of voice commands and their functions.

Figure 4.8 presents the user perspective of the developed interactive tool, illustrating the user-friendly and informative interface that integrates spectral imaging with AR. This interface allows users to observe all relevant characteristics of the spectral map projected on a digital model of the sample, offering a degree of contextualized interpretation and gesture-based interaction of the acquired data not achievable with traditional visualization methods. In particular from user experience, we highlight the following interaction capabilities:

- Moving and Rotating the sample: allowing to position and move freely the sample, analyzing in detail the composition from multiple perspectives;

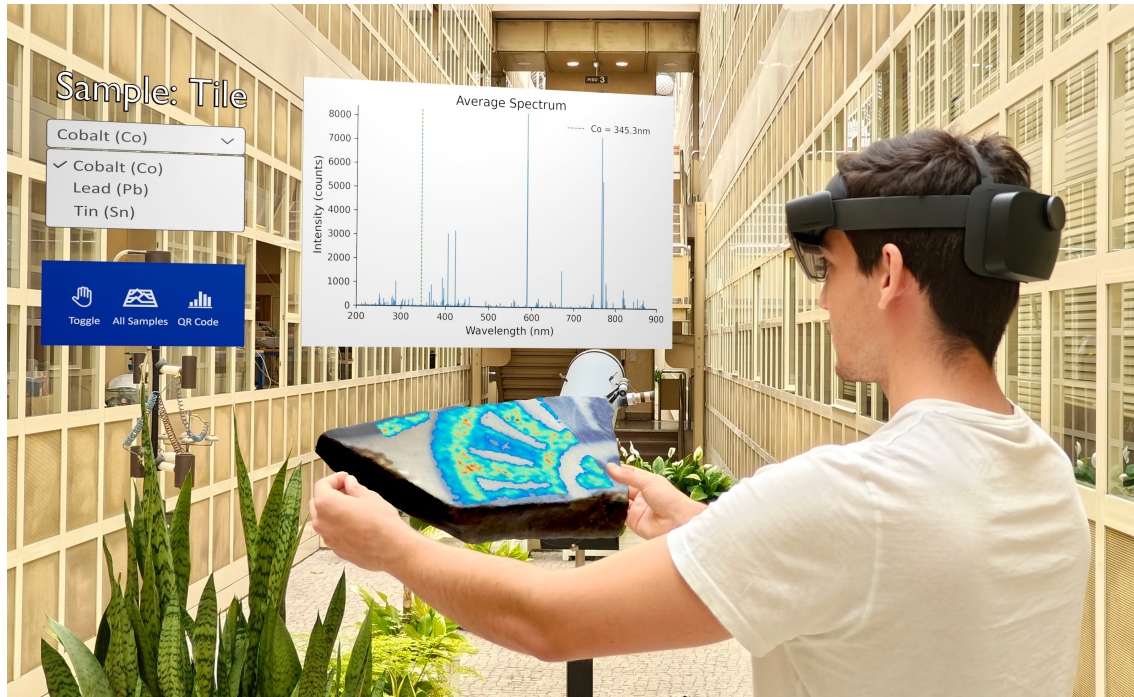


Figure 4.8: View simulating the user's perspective while wearing the HoloLens 2 and interacting with the developed interface. A video demonstration can be found in the reference [94].

- **Scaling:** allowing to scale up small samples or reducing larger ones, the solution offers unique perspectives of the samples in integration with additional spectral features;
- **Texture-based interpretation:** including the texture of the sample surface and possible roughness, it is possible to relate common signal variations (e.g. plasma signal in LIBS) due to surface properties and better contextualize them.
- **Multiple sample comparison:** adding multiple samples at the same time to the environment eases visual comparisons, enabling clear connections or distinctions.

4.1.3.2 Project 2: QR Code Integration for Dynamic Data Display

To enable streamlined and user-centric access to the data, we integrated a database together with a QR code access strategy to dynamically load 3D models and display corresponding information upon scanning. The key concept is that when a QR code is detected, the system can either present relevant data about the sample or load 3D models from a GitHub online repositories, for immediate visualization. This functionality is powered by the QR Code Tracking package provided by Microsoft, which is specifically designed for HoloLens 2 to track and recognize QR codes in MR environments [95].

To achieve these capabilities, the project is configured to detect and respond to three specific QR codes, each containing a predefined text message, for exemplification purposes: "Sample1", "Sample2", and "QR_MENU". When the QR codes with the messages "Sample1" or "Sample2" are scanned, the system displays two preloaded 3D models (a wrench and a rock, respectively) as depicted in Figure 4.9. In addition to these models an information panel appears, offering a brief description of the sample, highlighting its primary constituents, and also including an image that shows the spatial distribution of these elements within the sample, as determined by combining LIBS datasets with k-means clustering, as presented in reference [61].

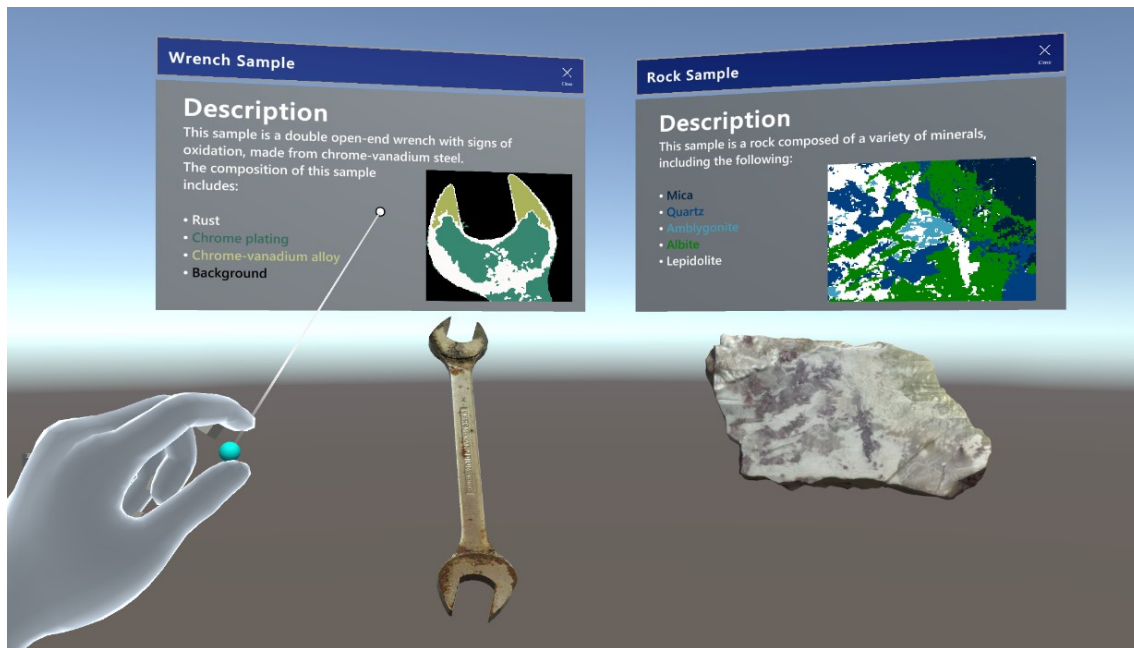


Figure 4.9: Informative panel after scanning the QR codes "Sample1" and "Sample2". View from the Unity interface.

This information panel is interactive, allowing the user to move it and close it as needed. The first time the QR code is scanned a text message is displayed, indicating the voice command that can be used to reopen the panel and view the sample information again. For convenience, one of the features added is that when the QR code is moved, the sample automatically follows it, maintaining its relative position. This functionality allows for the easy movement and relocation of 3D models. For example, if you are viewing the model in one room and then move to another room, the model will stay in the same spot relative to the QR code. To bring the model back to your immediate vicinity, you can simply scan the QR code again using a QR code displayed on your mobile device, for example, and the model will reappear, eliminating the need to manually transport models from room to room.

If the QR code contains the message "QR_MENU", scanning it will display a menu box listing all files in the .fbx and .obj formats that are present in the following GitHub directory: <https://github.com/RafaelCavaco/3D-Sample-Models>. Although the developed script is designed to detect both formats, the .fbx format is preferred since it contains information about the 3D models mesh, allowing to define directly a box collider, which enables the addition of manipulator object features (such as ObjectManipulator and NearInteractionGrabbable functions). Additionally, .fbx files require only the texture file, whereas .obj files also need a .mtl (Material Template Library) file, which contains information about material properties (including texture paths and base color).

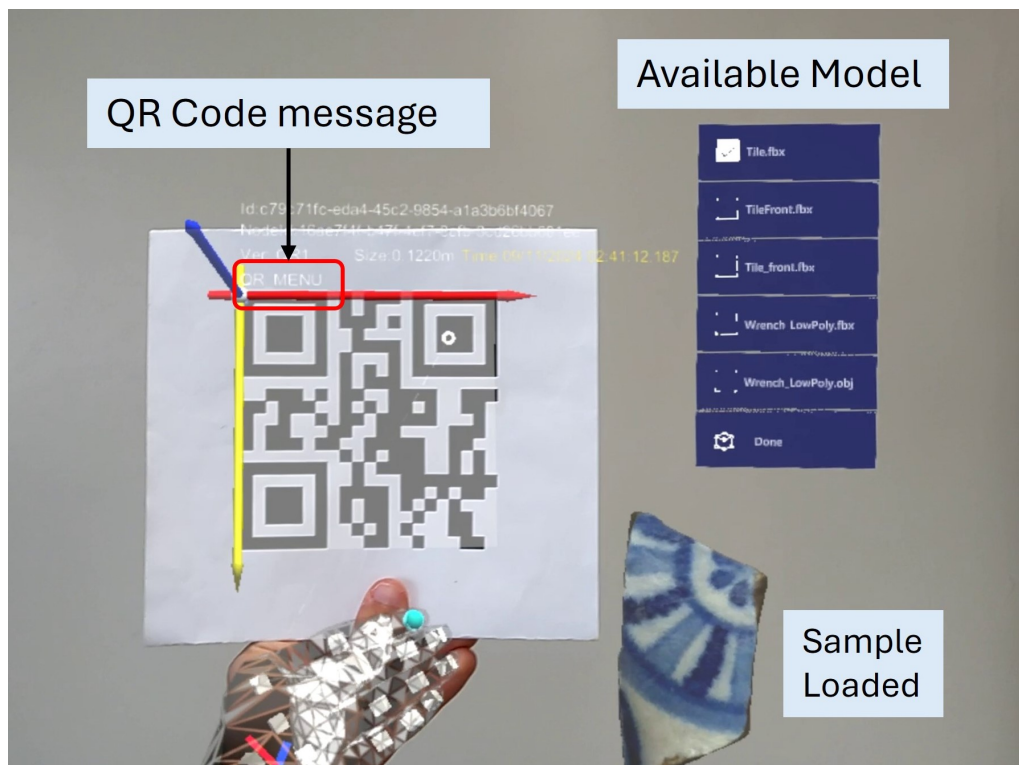


Figure 4.10: Panel displaying all available models after scanning the QR code with the message "QR_MENU", along with the appearance of a sample loaded from GitHub after being selected in the checkbox. The image is captured through the HoloLens 2 camera, providing a view from the perspective of the device.

When a model is selected via the checkbox, it is downloaded from GitHub and its texture is automatically applied if it is present in the "Textures" folder of the GitHub repository. To ensure correct texture referencing, textures must be saved in the Shading tab in Blender and placed in the "Textures" GitHub folder. Additionally, to facilitate bringing the objects into the scene, the TriLib model loading package was integrated, and the *InternetClient* functionality was enabled in the project settings.

4.2. Discussion and Outlook

Leveraging on these capabilities, the potential applications of this approach are vast and will be discussed in two major directions, in close connection with the samples presented: industrial applications and academic ones, with a focus on heritage science.

From an industrial perspective, the applications of this technology focus essentially on quality control and monitoring. As seen for the tool in Figure 4.8, LIBS imaging can identify and monitor material degradation, providing critical information for maintenance and conservation efforts. Integrated with AR, areas of corrosion or material fatigue may become more evident, inclusively allowing to establish a deeper connection with the object volume.

From an academic perspective, the applications are also compelling. Focusing on heritage science for illustrative purposes, the study of objects and artifacts strongly benefits from using spectral imaging techniques like LIBS as they offer sensitive and rapid spatial maps of chemical compositions with minimal sample preparation. With such a technique, the researcher can analyze paintings, metals, ceramics, and stones, providing detailed information about the composition of the object, which may aid in their characterization and inform the planning of preservation interventions. AR is also rather popular in this research domain, as it provides a means for users to visualize and interact with accurate digitized models of objects, allowing free gesture-based interaction without harming asset preservation [96]. Besides, it can transform cultural and educational experiences into engaging experiences, facilitating collaborative and inclusive environments among scholars using shared digital platforms regardless of their physical location [96–98].

In this context, the potential to add novel layers of information to digital models of heritage artifacts coming from spectral imaging technologies may enable deeper analysis and insights without physical interaction, contributing for example to a better yet harmless understanding of the materials and techniques used, as well as connections to the historical period [96]. The 3D interactivity may also be utilized to inform the planning of preservation strategies and to establish collaborative playgrounds with multiple layers of information and multiple samples (e.g. fragments [99, 100]).

All in all, besides the natural exploration of the tool in multiple domains of science and technology such as heritage research [96], biology and medicine [33, 47, 101], geology [102], and industrial process control [103], we anticipate that promising future research lines may also include the exploration of a few other ramifications including the exploration

of other spectral imaging techniques, with multimodality and sensor fusion; the integration of machine learning tools and solutions for analysis and sample classification; and the exploration of the tool in classroom settings for teaching and demonstration purposes.

4.3. Overview

This chapter introduced a comprehensive understanding of how spectral imaging can be effectively integrated into augmented reality environments, opening new possibilities for data visualization and analysis in an immersive, three-dimensional space. Two different projects were subsequently presented, dedicated to showcasing this integration: a spectral data analysis interface and a QR code integration system for dynamic data display.

These projects demonstrate the potential of combining spectral imaging with AR technology, offering new ways to interact with and analyze complex spectral data.

5. Embedding Spectral Images in real-world objects: preliminary results

While the previous chapter focused on visualizing and interacting with virtual elements in an AR environment, the work in this chapter seeks a first step towards a deeper level of integration between the digital and physical realms. In particular, we explore a concrete example of Mixed Reality, where virtual and real environments seamlessly interact and influence each other.

Specifically, this chapter presents our efforts to develop a solution to display spectral data overlaid on real physical objects, enabling dynamic interaction between virtual spectral information and tangible items in the user's environment.

5.1. Towards Real-Time Spectral Data Overlay on Physical Objects

To achieve the objective set for this chapter, we adapted the pipeline presented in the previous chapter (Figure 4.1), building upon the capabilities and similar models. Yet, instead of simply displaying models with overlaid spectral images, we now need to enable the real-time detection of previously scanned 3D objects (the physical sample itself) to overlay the spectral imaging data directly onto these objects, also acting as spatial anchors.

To fuse spectral imaging data with 3D objects in real-time, VisionLib software [104] was employed to identify the corresponding object in the real world using its 3D model as a reference. VisionLib is a powerful tool for object recognition that employs computer vision techniques to locate desired objects within the camera image and utilizes simultaneous localization and mapping (SLAM) techniques to reconstruct maps of the current environment helping to mitigate loss in tracking- when the model exits the camera field of view or if the camera is moved very abruptly and rapidly- by estimating the device-relative object poses from model-based tracking. Matching the model edges with edges detected in the camera image stream allows for accurate recognition and tracking of 3D models in the physical world.

In practice, the pre-loaded 3D model of the object is initially displayed in the scene and then manually adjusted within the HoloLens 2 interface to match the position of the real object. Once the 3D model is properly aligned and recognized ("tracked" state), a C# script is used to remove the virtual model from the scene, leaving only the physical object

visible. At this point, the spectral imaging data is overlaid directly onto the real object (i.e., replacing the 3D model position), accurately conforming to its contours and surface characteristics.

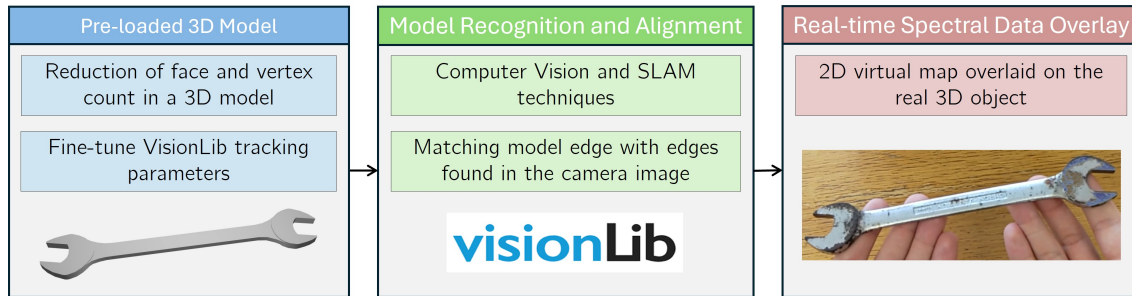


Figure 5.1: Procedure used to obtain spectral data overlay on physical objects.

To further improve and optimize object tracking, two procedures were implemented: i) adjustment of the parameters offered by VisionLib and ii) simplification of the model.

Starting with the available parameters, various settings that could significantly impact the quality of model tracking were tested, including **laplaceThreshold**, **NormalThreshold**, and **keyFrameDistance**:

- **laplaceThreshold**: This parameter controls the sensitivity of edge detection in the model. By fine-tuning this threshold, users can balance between detecting finer details and reducing noise, which affects the precision and stability of the tracking.
- **NormalThreshold**: This parameter influences how sensitive the tracking is to the orientation of the object's surfaces. Proper adjustment ensures that the system accurately tracks objects with varying surface angles while avoiding instability in complex geometries.
- **keyFrameDistance**: This parameter defines how frequently keyframes are generated during tracking. Adjusting the keyFrameDistance allows for better tracking accuracy during object movement, while also managing the computational load for optimal performance.

By adjusting these parameters, it is possible to achieve higher-quality tracking while minimizing the processing load on the HoloLens 2.

To enable dynamic interaction with these parameters without the need for constant deployment after each modification in the .vl file (the file format where the parameters are adjusted), the **HoloLens2ModelTrackingSetup** scene was used, allowing for real-time

testing and adjustment of the parameters. In this context, numerous parameters were varied across both samples studied until reasonable model tracking was achieved. For the two models utilized as case studies (wrench and rock samples), the parameters that were empirically found to be the most suitable were the following:

```
"keyFrameDistance": 50,
"laplaceThreshold": 10,
"normalThreshold": 0.3,
"maxFramesFeaturePrediction": 3,
"extendibleTracking": true,
"useColor": false
```

In addition to adjusting the tracking parameters, the model was also simplified in Blender to minimize processing latency. Since the models imported from ParaView contained a large number of faces and vertices, as mentioned in Section 4.1.2, the number of these parameters needs to be reduced to facilitate their recognition. It is however important to note that this process is different from the previous described in the last chapter, where only vertices and faces that did not contain relevant information for the spectral images were removed. Here, the face reduction was applied directly to the 3D model itself, altering its structure and smoothing its roughness.

To achieve this, a *Decimate Modifier* may be applied, specifically using the *Planar mode*. This filter reduces details on forms comprised of mainly flat surfaces, significantly reducing the number of faces and vertices and making the model easier to process. To apply this in Blender, we can go to *Modifier -> Add Modifier* and apply a *Decimate* block, further selecting *Planar* and setting the angle to 10 degrees. The resulting simplified model (see step 1 of the procedure in Figure 5.1 left) was able to be recognized in the HoloLens 2 device, achieving the results shown in Figure 5.2, illustrating the spectral data overlay.

This method enables a seamless integration of digital spectral data on real-world samples, providing an enhanced interactive experience. Similarly to the previous interface, this project also includes a dropdown menu allowing the user to select the spectral imaging overlay for the sample. When the user selects a specific feature or spectral map, the corresponding data is immediately projected onto the physical object, also allowing for in-depth analysis and exploration.



Figure 5.2: Illustration showing the overlay of virtual spectral data onto tangible objects in the user's environment, specifically for the wrench and rock samples.

Furthermore, since the tracking occurs in real-time, any movement of the physical sample is dynamically followed by the spectral imaging data, ensuring that the overlay remains consistent and aligned with the object. However, this time, the overlay is constrained to the dimensions of the physical model, and transformations like rotation or scaling are not allowed.

5.2. Discussion and Outlook

Despite many of the functionalities described in the previous chapter being applicable here, this approach also holds significant implications for applications where direct interaction with physical samples is necessary. The ability to interact with physical objects in real-time significantly enhances the potential applications of this technology, particularly in industrial and manufacturing settings for tasks such as quality control and monitoring in production processes.

In the context of scientific research or heritage conservation, the ability to overlay spectral data onto physical objects becomes a crucial tool for assessing material properties on-site, providing immediate visual feedback of the sample features aligned with real-world conditions. This capability extends to mining and geology, where it enables mineral characterization directly on-site without the need for destructive testing or physical contact, preserving artifacts and samples.

Furthermore, in the realm of quality control, MR can guide maintenance personnel through complex inspection processes by overlaying spectral data onto physical components to highlight areas requiring attention, thus improving worker efficiency. This holds potential essentially for upstream interventions, including the detection of production defects and ensuring product quality by detecting elemental inconsistencies or contaminations. It can

also assist in classifying and sorting samples based on their properties. For instance, materials could be instantaneously selected by the user in different production lines based on their spectral characteristics, thereby streamlining processes and improving overall efficiency.

5.3. Concluding Remarks

This chapter reported the initial steps of a solution to embed spectral images in real-world objects using MR, demonstrating how virtual spectral data can dynamically interact with tangible items. By integrating VisionLib for object recognition and leveraging real-time tracking, we were able to overlay spectral imaging data directly onto physical objects, effectively merging the digital and physical environments. This approach goes well beyond previous methods by allowing users to actually *see what their eyes cannot*, engaging with data in a more intuitive and contextually relevant manner, enhancing the potential for analysis and interaction.

The results illustrate a seamless alignment of digital data with the physical objects, maintaining consistent overlay even during object movement. This achievement paves the way for new opportunities for context-aware data visualization with impact in various fields such as industrial manufacturing, quality control, heritage conservation, and scientific research.

6. Final remarks and future works

In this work, we committed to developing a solution to integrate spectral imaging data into extended reality environments, aiming to enhance user capabilities and address the limitations in the interaction with spectral imaging datasets. In particular, we aimed at two operational objectives, centered on developing two full-stack processing pipelines and software solutions for Augmented and Mixed Reality.

For that purpose, in the first part of the work we introduced the basic concepts of spectral imaging, mapping the typical processes involved. Utilizing LIBS as a specific example of a spectroscopy technique, we covered the major features and working principles of the technique, along with practical applications. Proceeding towards the goal of building 3D digital models, we also described the process of spectral dataset capture, data preprocessing, and the methodology for generating 3D models and aligning them with spectral images. In the subsequent chapter, the concept of extended reality was also introduced, presenting an overview of XR devices with a deeper focus on the HoloLens 2 head-mounted device, the one used in this project, highlighting its specific features, specifications, and applications.

In the second part, we proceed by describing our efforts, methodology, and features of the two full-stack solutions developed. The first solution introduced a data acquisition and digital model construction pipeline together with an immersive analysis interface. Merging 3D models with interactive 2D spectral maps, it may facilitate comprehensive exploration, allowing users to examine detailed patterns and perform comparative analysis. Besides, by enabling dynamic manipulation of models, users can interact with samples from various perspectives, enhancing the overall analytical experience. In order to allow a more streamlined utilization by end-users, we also explored the integration of QR codes for dynamic 3D model loading and data visualization of preload assets. By scanning QR codes, users can access and visualize previously constructed models loaded directly from GitHub repositories, with the added flexibility of relocating models based on the QR code position.

Building on the foundation of the first project, the MR project incorporated real-time spectral data overlayed onto physical objects by employing VisionLib software. This project achieved accurate object recognition and tracking, allowing spectral data to be projected onto real-world samples with real-time interaction.

Collectively, these projects demonstrate the potential of augmented and mixed reality technologies to transform spectral data analysis, offering intuitive and interactive solutions that bridge digital and physical environments. The use of QR codes for dynamic data display and the real-time overlay of spectral information on physical objects underscore the flexibility and practical applications of these methodologies. These advancements not only facilitate deeper insights into material properties but also can support enhanced learning and analysis in diverse contexts.

6.1. Perspectives and Future Works

Although time constraints prevented the full development of some intended functionalities, the results achieved underscore the significant potential of combining XR with spectral imaging techniques. The applications developed allow for more intuitive and detailed analysis, paving the way for future improvements and expansions at three levels: hardware, software, and applications (see Figure 6.1).

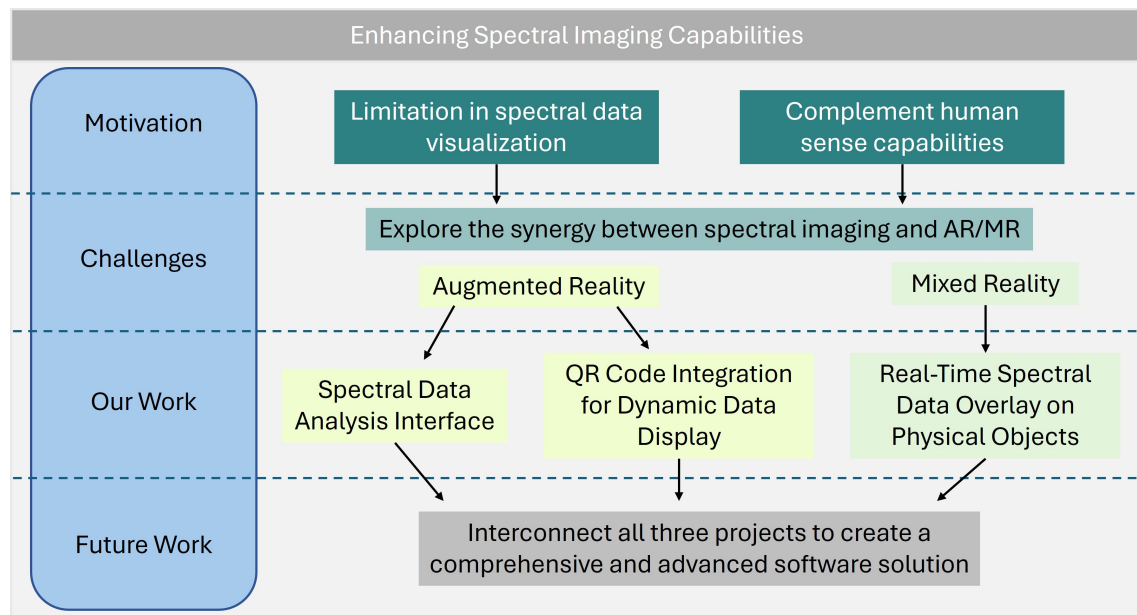


Figure 6.1: Visual summary of the project's motivation, key challenges, work completed, and future directions, highlighting the integration of spectral imaging with augmented and mixed reality.

First, looking from the hardware perspective, future work could focus on fully automating the spectral analysis acquisition and 3D model digitalization and construction. The development of hardware integrating a spectroscopy technique together with a 3D scanner solution would allow a more streamlined acquisition of datasets and analysis of samples. For instance, the process could start with generating a 3D model in a dedicated and precise system. This model could then be transferred to the LIBS setup via the stage,

where, as spectral data is captured, some spectral images would be generated based on automated qualitative analyses. Besides, it can improve the automation of 3D model alignment with spectral images, possibly through the use of clustering techniques to enhance pattern recognition and data overlay. The 3D model and spectral images could be uploaded to GitHub and displayed on the HoloLens 2, allowing users to download them through Project 2, which is partially designed for model loading functionality.

When looking from the software point-of-view, a key improvement would be to interconnect the projects as a unique and seamless workflow. For instance, enabling communication between the HoloLens 2 and a computer via Python could facilitate wireless data transfer, especially for dynamic datasets. Also, developing a collaborative analysis platform where multiple users can simultaneously interact with and manipulate data and models in a shared environment would be valuable. Another topic of interest is to explore methods to solve potential inaccuracies in feature selection due to resolution limitations. One alternative possibility for the alignment could be performed in Python using feature clustering techniques on both the spectral imaging and the 3D model, effectively aligning the features and consequently the model with the 2D image.

Finally, from the side of applications, we believe the path is now paved for a multitude of real-world applications. Indeed, this project has not only contributed to the advancement of visualization tools in the context of spectral imaging but also provided valuable learning experiences in using various software and technologies (essentially ParaView, Blender, and Unity), solidifying AR and MR as a powerful tool for science and research. Illustrative examples that can be explored include building interactive digital twins of heritage artifacts, exploring the integration of such tools for teaching purposes in order to better introduce spectral imaging tools for non-specialized audiences, or the development of in-line monitoring solutions with integrated dashboards for industrial applications.

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A. Appendix A

This Appendix provides a set of scripts designed for aligning 3D models in ParaView and subsequently simplifying them in Blender, which is especially essential when working with large datasets or complex models that require efficient handling in different software environments.

A.1. Mesh Matching Algorithm

The procedure to align the 3D model with the mesh begins by adding the model to ParaView and applying its texture as a reference for the features. Next, the user selects a number of points they consider essential and runs the first script. This script simply saves the coordinates of the selected points in the matrix "p_mesh".

```

1 from paraview.simple import *
  import numpy as np
3
  mesh = GetActiveSource()
5 es = ExtractSelection()
  dataset = servermanager.Fetch(es)
7 n_selected_points = dataset.GetNumberOfPoints()
  p_mesh = [dataset.GetPoints().GetPoint(i) for i in range(0, n_selected_points)]

```

Next, the same procedure is applied for the VTK file containing the spectral imaging information, now saving the mesh points in the matrix "q_mesh". It is important to select the same number of points as before, ensuring that they correspond to the same features in the model. The selected points are analyzed to determine the optimal transformation that minimizes the distance measured using the Manhattan metric between the model points and the mesh points after the transformation. Thus, the minimum distance is selected, and the corresponding transformations are applied to a new VTK mesh, as shown in the following script:

```

  from paraview.simple import *
2 from vtk.util.numpy_support import *
  import vtk
4 import numpy as np
  from itertools import permutations

```

```

6
    distances = []
8
    ts = []
    rs = []
10
    cs = []

12
    slice1 = GetActiveSource()
    es = ExtractSelection()
14
    dataset = servermanager.Fetch(es)
    n_selected_points = dataset.GetNumberOfPoints()
16
    p_slice = [dataset.GetPoints().GetPoint(i) for i in range(0, n_selected_points)]

18
    es = ExtractSurface(Input = slice1) # Extracts all points from VTK mesh
    dataset = servermanager.Fetch(es)
20
    n_points = dataset.GetNumberOfPoints()
    libs = dataset.GetPointData().GetArray("Libs")
22
    all_points = [dataset.GetPoints().GetPoint(i) for i in range(0, n_points)]
    libs_array = np.array([libs.GetValue(i) for i in range(0, n_points)])
24

    #Combinations of Points
26
    arrays_points = np.array(list(permutations(p_slice)))
    p_matrix = np.array(p_mesh)
28
    def alignment(A, B):
        """
30
        Function that determines the R, c, t parameters between two matrices
        """
32
        assert A.shape == B.shape
        n, m = A.shape
34

        EA = np.mean(A, axis=0)
36
        EB = np.mean(B, axis=0)
        VarA = np.mean(np.linalg.norm(A - EA, axis=1) ** 2)
38

        H = ((A - EA).T @ (B - EB)) / n
40
        U, D, VT = np.linalg.svd(H)
        d = np.sign(np.linalg.det(U) * np.linalg.det(VT))
42
        S = np.diag([1] * (m - 1) + [d])

44
        R = U @ S @ VT

```

```

    c = VarA / np.trace(np.diag(D) @ S)
46     t = EA - c * R @ EB

48     return R, c, t

50 # Calculates R, c, t and computes the distance relative to matrix p
    for i in range(len(arrays_points)):
52         q_matrix = arrays_points[i]

54         R, c, t = alignment(p_matrix, q_matrix)
            rs.append(R)
56         cs.append(c)
            ts.append(t)
58         mapped_xyz = np.array([t + c * R @ i for i in q_matrix])

60         distances.append(np.sum(np.abs(mapped_xyz - p_matrix)))

62 index = np.argmin(distances)
    ideal_R = rs[index]
64    ideal_t = ts[index]
    ideal_c = cs[index]
66

    # Apply the transformation to each point in the mesh
68    mapped_xyz = np.array([ideal_t + ideal_c * ideal_R @ i for i in all_points])

70 # Create VTK grid and points and fill it with transformed coordinates
    ug = vtk.vtkUnstructuredGrid()
72    pts = vtk.vtkPoints()

74 # Fill the new grid with transformed coordinates
    mapped_vtk = numpy_to_vtk(mapped_xyz, deep=True)
76    pts.SetData(mapped_vtk)
    ug.SetPoints(pts)
78

    # Fill the new grid with intensities extracted from VTK
80    libs_vtk = numpy_to_vtk(libs_array, deep=True)
    libs_vtk.SetName('Libs')
82    ug.GetPointData().AddArray(libs_vtk)
    ug.GetCellData().AddArray(libs_vtk)

```

A.2. Script for Removing Transparent Faces in 3D Models

This script automates the process of identifying and removing faces with transparent textures from 3D models in Blender. The procedure is straightforward: simply add the names of all the models you wish to simplify to the *mesh_names* list and provide the directory of the texture image. When the script runs, it iterates through all the faces of the models and removes the ones with transparent textures, leaving only the essential information in the 3D models.

```

1 import bpy
  import bmesh
3 import numpy as np
  from PIL import Image
5
  # List of mesh object names and path to the image file
7 mesh_names = ["mesh1", "mesh2", "mesh3", "mesh4", "mesh5"]
  image_path = 'Textures/modified_colormap.png'
9 image = Image.open(image_path).convert('RGBA')
  image_data = np.array(image)
11
  for mesh_name in mesh_names:
13     obj = bpy.data.objects.get(mesh_name)
        mesh = obj.data
15
        uv_layer = mesh.uv_layers.active.data
17     bm = bmesh.new()
        bm.from_mesh(mesh)
19
        faces_to_remove = []
21
        # Check each face in the mesh
23     for face in bm.faces:
        transparent_face = True
25         for loop in face.loops:
            uv_coords = uv_layer[loop.index].uv
27             height, width, _ = image_data.shape
            x = int(uv_coords[0] * width)
29             y = int((1 - uv_coords[1]) * height)
            x = max(0, min(x, width - 1))

```

```
31     y = max(0, min(y, height - 1))
    pixel_color = image_data[y, x]
33
    # If the alpha value (pixel_color[3]) is not zero, the face is not
    fully transparent
35     if pixel_color[3] != 0:
        transparent_face = False
37         break
39
    # Mark face for removal if it is fully transparent
    if transparent_face:
41         faces_to_remove.append(face)
43
    if faces_to_remove:
        bmesh.ops.delete(bm, geom=faces_to_remove, context='FACES')
45
    bm.to_mesh(mesh)
47    bm.free()
```

B. Appendix B

For the purpose of the work presented in this dissertation, we utilized the Unity version 2020.3.34f1 (64-bit). This appendix aims to provide a guide to setting up a project like the ones described in the main text, serving as a reference for future users and warranting the future reproducibility of the work.

B.1. Set up a new OpenXR project with MRTK

Configuring a project correctly is essential to ensure it functions as intended on the target platform. In Unity, specific settings must be adjusted to optimize the project for deployment on HoloLens 2 devices. For our project, the process began with creating an empty 3D project. Once created and opened, we navigated to **File -> Build Settings** and selected **Universal Windows Platform (UWP)**. Here, the **Target Device** was set to **HoloLens**, and the **Architecture** was configured for **ARM64**, ensuring compatibility with the device's specifications [105].

Next, several tools from the Mixed Reality Feature Tool were added to the project. Specifically, the **Mixed Reality Toolkit Foundation** and the **Mixed Reality OpenXR Plugin** were integrated. In addition to what has already been mentioned, this package offers an extensive array of tools and prefabs, including menus, buttons, panels, and sliders, all of which are essential for building intuitive and interactive interfaces. Each of these prefabs can be customized to fit the specific needs of the project, streamlining the development process and enhancing the user experience.

Once this process is completed, Unity will prompt you to restart the project to apply the selected packages. After restarting, you will have access to the chosen tools. The next step is to go to **Edit > Project Settings**, select **Initialize XR on Startup**, and then, under Plugin Providers, select **OpenXR**. This action will reveal multiple options under OpenXR, where you will need to select the **Microsoft HoloLens feature group**.

In the XR Plug-in Management section, ensure OpenXR is opened. To enable specific interaction capabilities, click on the "+" sign under **Interaction Profiles** and add the desired profiles. For this project, the **Eye Gaze Interaction Profile** and **Microsoft Hand Interaction Profile** were chosen. Additionally, the **Depth Submission Mode** was set to **Depth 16 Bit** to optimize depth perception in the application.

Finally, you can also choose the **Product Name** in **Project Settings** —this is the name that will appear for the application on the HoloLens 2.

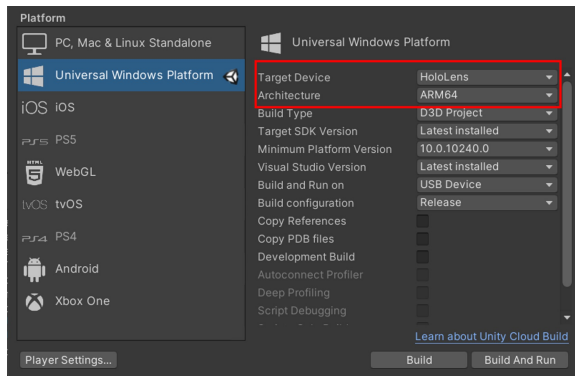


Figure B.1: Build Settings.

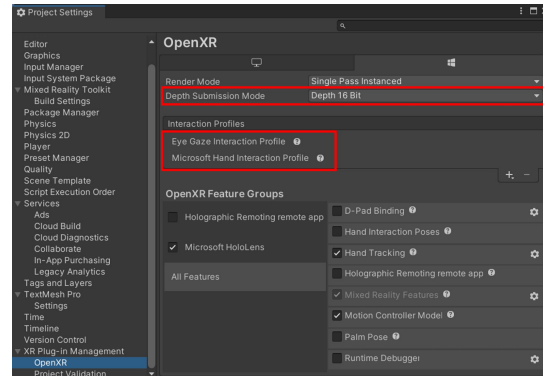


Figure B.2: Project Settings.

B.2. Project Deployment

After completing the development phase in Unity, the next crucial step is to deploy the project to the HoloLens 2 device. This process involves several key steps to ensure that the application runs smoothly on the device.

First, within Unity, you need to build the project through the Build Settings interface. It is common to create a dedicated folder to store all the files generated during the build process to help keep the project files tidy and easily accessible. Once the build is complete, the next step is to open the generated .sln file using Visual Studio 2019. It is important to note that not all versions of Visual Studio are compatible with HoloLens 2, which is why an older, stable version like 2019 is preferred for this process. Within Visual Studio, you will need to adjust some configurations to ensure the project is properly set up for deployment. Navigate to **Project -> Properties**, and at the top of the **Configuration** tab, set the Configuration to **Release** and the Platform to **ARM64**. Since the deployment to HoloLens 2 is done over WiFi, it's necessary to configure the correct IP address of the HoloLens device. To do this, locate the **Machine Name** field under **Project -> Properties -> Debugging** and input the IP address of the HoloLens 2. To find the correct IP address, go to **Settings -> Update & Security -> For Developers** on the HoloLens 2 device. The IP address can be found next to the "https://" prefix, and this should be entered exactly as displayed.

After these configurations are set, the project can be deployed from Visual Studio to the HoloLens 2. It is important to ensure that the HoloLens 2 is connected to the same network as the development machine to facilitate a seamless transfer. Once deployed, the

application will start running on the HoloLens 2.