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MASTER's Degree in BIOMEDICAL ENGINEERING

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Augmented reality for surgical planning: integrating Hololens 2 for 3D visualization and interaction with patient-specific anatomical models

Supervisors

Prof. Massimo SALVI

Co-Supervisors

Prof. Kristen M. MEIBURGER

Eng. Francesco MARZOLA

Prof. Alberto AREZZO

Candidate

Chiara PES

JULY 2025

Declaration

I hereby declare that the contents and organization of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

Turin, 21/07/2025

* *This dissertation is presented in partial fulfillment of the requirements for Master's degree in the Bioengineering course of Polytechnic of Turin*

AI use Disclosure

In the writing process of this thesis the following tools have been used to improve readability and language:

- Grammarly (Grammarly, Inc.)
- ChatGPT (OpenAI)

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Summary

Augmented reality (AR) is an emerging technology with significant potential to improve preoperative surgical planning by optimizing spatial understanding of patient-specific anatomy. This thesis presents the development and initial evaluation of an integrated system leveraging Microsoft HoloLens 2 for immersive 3D visualization and interaction with anatomical models reconstructed from thoracic computed tomography (CT) scans, specifically for planning lung biopsy procedures.

The system architecture is based on an integration between the 3D Slicer medical image computing platform and a custom Unity application developed for HoloLens 2. Communication is facilitated by the OpenIGTLink protocol, enabling dynamic streaming of CT slice data and spatial transformations. Anatomical structures, including lungs, nodules, the bronchial tree, vasculature, and ribs, are automatically segmented from CT data using a nnU-Net, TotalSegmentator, within 3D Slicer and subsequently exported as 3D models. These models are imported into Unity and rendered as interactive holograms in the HoloLens 2 environment, controlled via a custom user interface based on the Mixed Reality Toolkit (MRTK).

Key functionalities include dynamic loading and manipulation of 3D models, real-time synchronized visualization of CT slices through the holographic models, and simulation of optimal biopsy needle trajectories. This work details the system's architecture, the implementation of the 3D Slicer planning module, the AR application in Unity, and discusses the technical considerations for integrating these tools. Preliminary usability feedback from clinicians is also presented, highlighting the system's potential to improve preoperative planning accuracy and spatial awareness, and potentially reduce reliance on intraoperative imaging.

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Acronyms

AI
: Artificial Intelligence

AR
: Augmented Reality

CT
: Computed Tomography

MRI
: Magnetic Resonance Imaging

HMD
: Head-Mounted Display

MRTK
: Mixed Reality Toolkit

nnU-Net
: No-New-Net U-Net

OpenIGTLink
: Open Network Interface for Image-Guided Therapy

3D
: Three-Dimensional

2D
: Two-Dimensional

VR
: Virtual Reality

MR
: Mixed Reality

DL
: Deep Learning

CNN
: Convolutional Neural Network

PAA
: Percutaneous Approach Analysis

IGS
: Image-Guided Surgery

LIDC-IDRI
: Lung Image Database Consortium and Image Database Resource Initiative

LUNA16
: Lung Nodule Analysis 2016

UWP
: Universal Windows Platform

XR
: Extended Reality

TCP/IP
: Transmission Control Protocol/Internet Protocol

HPU
: Holographic Processing Unit

IMU
: Inertial Measurement Unit

DSC
: Dice Similarity Coefficient

NSD
: Normalized Surface Distance

BSP
: Binary Space Partitioning Tree

VTK
: The Visualization Toolkit

GUI

Graphical User Interface

RAS

Right-Anterior-Superior

MVC

Model-View-Controller

CI

Confidence Interval

GPU

Graphics Processing Unit

UI

User Interface

Chapter 1

Introduction

1.1 Context and motivation

In recent years, thoracic surgery has seen a progressive increase in procedures aimed at small pulmonary nodules diagnosis and treatment. These are often identified thanks to the development of imaging techniques. However, accurate localisation of these lesions remains challenging both preoperatively and during surgery or biopsy [1]. Augmented reality (AR) has emerged as an emerging technology capable of supporting the surgeon in planning and performing complex procedures, improving spatial understanding of anatomical structures, and reducing error margins. In parallel, advances in artificial intelligence (AI) and automated anatomical segmentation have opened new perspectives for rapid and accurate customisation of three-dimensional (3D) patient models. Devices such as the Microsoft HoloLens 2 have been developed to integrate real-time 3D visualisations directly into the surgeon's field of view, thereby improving intraoperative orientation without compromising the continuity of the surgical procedure. The integration of AR, AI, and medical imaging signifies a highly promising domain for enhancing preoperative planning and safety in minimally invasive thoracic surgery.

1.2 Project objectives

The aim of this thesis project is to develop an integrated system for the AR visualisation of 3D anatomical models reconstructed from thoracic computed tomography (CT) scans. The system has been developed for the specific purpose of supporting the accurate localisation of pulmonary nodules during preoperative planning.

The objectives of the project are as follows:

- Implement automated segmentation of pulmonary nodules and key thoracic structures (including the bronchi, blood vessels, and rib cage).
- Simulate and evaluate optimal trajectories for biopsy needle placement. A virtual environment will be used to plan safe and effective access paths to the target nodules.
- Integrate and visualise the segmented 3D models in a mixed reality environment, utilising Unity and OpenIGTLink to deploy patient-specific anatomical data on the HoloLens 2 headset.

- Design and develop dual user interfaces: one embedded in the 3D Slicer platform to support desktop-based interaction and processing, and another in the Unity AR scene, featuring an intuitive virtual menu for direct manipulation of models in the AR space.
- Conduct preliminary validation of the system through qualitative feedback collected from experienced thoracic surgeons in order to assess its usability, clarity, and clinical relevance.

The development will be initiated within a controlled, simulated environment and subsequently expanded to semi-real clinical scenarios using anonymised patient data.

1.3 Thesis Goals

The main objectives of this thesis are to:

- Demonstrate the feasibility of using HoloLens 2 AR to improve both preoperative lung nodule localization and the guidance of the biopsy procedure itself.
- Evaluate the potential clinical impact of the integration of automatic segmentation, trajectory planning, and AR visualisation on thoracic surgery practice.
- Determine the current limitations of the technologies used (e.g., spatial registration accuracy, segmentation accuracy, data transfer latency).
- Suggest possible future developments for clinical implementation on a wider scale.

This work aims to explore AR's potential to enhance surgical planning and pave the way for future AR-assisted intraoperative applications.

Chapter 2

Background

2.1 Thoracic surgery and preoperative planning

Technological advances in medical imaging and visualisation are radically transforming surgical planning and execution. In particular, the integration of medical planning software, such as 3D Slicer, with advanced visualisation devices like (MR) viewers - for example, the Microsoft HoloLens 2 - is opening new frontiers for improving the accuracy and safety of surgical procedures [2]. This is particularly relevant in complex specialties such as thoracic surgery, where a precise understanding of 3D anatomy and meticulous planning are essential for successful surgery. AI-assisted surgery and immersive display technologies, including virtual reality (VR), AR, and MR, are becoming increasingly important [3]. They can transform traditional two-dimensional (2D) medical images, such as those derived from CT, into interactive 3D models that facilitate surgical teaching, preoperative planning, and simulation. The aim is to provide surgeons with a clearer, more intuitive view of a patient's anatomy, enabling them to precisely locate lesions, identify critical anatomical structures, and anticipate potential complications.

Thoracic surgery involves a variety of procedures for treating diseases of the thorax, primarily those affecting the lungs (e.g., pulmonary nodules) and the chest wall [3] [4] [5]. One of the main challenges in this field is the precise localisation and effective resection of lesions, particularly when they are small, deep or non-palpable, as is often the case in minimally invasive procedures. Accurate identification, segmentation, and classification of pulmonary nodules is required to determine their benign or malignant nature and plan the most appropriate therapeutic approach.

Preoperative planning, therefore, plays a critical role in determining the outcome of thoracic surgery. Traditionally, this phase is based on the analysis of 2D CT images, which require the surgeon to mentally reconstruct the patient's anatomy in three dimensions. This approach has limitations when it comes to visualising complex spatial relationships, and it may be inadequate for detailed planning, particularly in complex cases or when minimally invasive techniques are used.

The advent of advanced visualisation technologies has provided new tools for overcoming these limitations. As discussed in [3] and [5], 3D reconstruction from CT images allows for the creation of patient-specific anatomical models that facilitate a more intuitive understanding. These 3D models can be used to:

- **Accurately locate pulmonary nodules:** identify the precise location, size, and relationship of the nodule to surrounding structures.

- **Identify critical anatomical structures:** visualise blood vessels, bronchi, and other structures that need to be preserved during surgery.
- **Simulate surgery:** plan the safest and most effective access trajectories, define resection margins, and simulate surgical procedures such as lung deflation or instrument placement.
- **Support therapeutic decisions:** for example, assess the feasibility of a segmentectomy versus a lobectomy or a wedge resection.

Integrating these 3D models into AR or MR systems is another step forward. Such systems for thoracic surgical planning or chest wall surgery allow surgeons to superimpose 3D holograms of patient anatomy directly onto the operating field during the planning phase. This improves spatial perception and can help define safer and more accurate surgical strategies.

The work in [2], although focused on pedicle screw placement planning, demonstrates the feasibility and usefulness of real-time integration between image processing software such as 3D Slicer and AR devices such as HoloLens 2 for interactive surgical planning, a concept that potentially extends to thoracic surgery as well.

The accuracy of these 3D models depends heavily on the quality of the input imaging data and the segmentation algorithms used. Several studies, along with reference datasets such as LIDC/IDRI [6] and LUNA16 [7], highlight the importance and challenges of automatically or semi-automatically detecting and segmenting lung nodules using deep learning (DL) techniques. These computational tools are essential for extracting relevant anatomical information from CT scans and generating 3D models for advanced surgical planning and AR-based navigation systems.

2.2 Augmented reality (AR) in surgery: state of the art

AR is an emerging transformative surgical technology that aims to improve surgical perception and accuracy by overlaying digital information, such as 3D anatomical models, surgical plans, and navigation data, directly onto the surgeon's view of the surgical field. This differs from VR, which immerses the user in a fully simulated environment, and MR, which allows deeper interaction between real and virtual objects.

The current state of AR in surgery includes a variety of applications and areas of development. One of the main applications is intraoperative surgical navigation. AR systems can project 3D models of the patient's anatomy, reconstructed from preoperative images (CT or MRI scans), directly onto the patient's body or into the surgeon's field of view via specific viewers, such as head-mounted displays (HMDs), like the Microsoft HoloLens. This enables target structures (e.g. tumours or nodules) to be more accurately located and critical structures (e.g. blood vessels or nerves) to be avoided, as demonstrated in various contexts, including thoracic surgery [4] [5], robotic liver surgery [8], neurosurgery [2], and chest wall surgery [4].

For instance, in thoracic surgery, such tools can utilize headsets like HoloLens to enable surgeons to visualize and interact with patient-specific thoracic anatomy, even allowing for simulations such as lung deflation. In other applications, like chest wall surgery, MR systems can provide holographic overlays of real-time, reconstructed 3D images for navigation, sometimes employing video pass-through HMD. Furthermore, the real-time integration of planning software (e.g., 3D Slicer) with AR devices demonstrates how planned data can be visualized to guide surgical procedures, with principles that can be adapted across multiple specialties.

Another significant area of application is medical and surgical training [9]. AR provides dynamic and interactive learning environments, transforming medical education—particularly in the teaching of anatomy. Tools such as the HoloLens 2 can enhance anatomy lab courses by offering students a more immersive experience and enabling the exploration of complex anatomical structures in 3D. AR is also used to improve surgical ergonomics and reduce cognitive load. By projecting relevant information directly into the surgeon's field of vision, there is less need to look away from the patient to consult external monitors. This can lead to greater concentration and potentially reduce operating time.

Finally, research is moving towards increasingly integrated and intelligent AR systems. For instance, a recent review analyzed the progress made over the last few decades in the field of image-guided surgery (IGS) systems, particularly those utilizing magnetic resonance imaging (MRI), highlighting trends in hardware, data visualization, and interaction methods [10]. The integration of AR with other technologies, such as intraoperative fluorescence or ultrasound, is also an active area of development, as suggested by discussions on image-guided liver surgery [8]. Despite these advances, significant challenges remain. These include ensuring registration accuracy between the real and virtual worlds, effectively managing soft-tissue deformation during procedures, addressing the ergonomics of HMD devices for prolonged surgeries, and managing implementation costs. Nevertheless, continuous technological development and the growing body of clinical studies suggest a promising future for AR as a standard tool in surgical practice.

2.3 Artificial intelligence (AI) for anatomical segmentation

Recent years have seen a growing role for AI, and in particular (DL) techniques, in the field of medicine. These techniques have been instrumental in revolutionising medical image analysis and anatomical segmentation [Marinakis et al., 2024, [11]]. Anatomical segmentation, i.e. the process of identifying and delineating the boundaries of organs, lesions or other structures of interest within images such as CT scans, is a critical step. It is fundamental for numerous clinical applications, ranging from diagnosis to monitoring disease progression, to the creation of patient-specific 3D models that are at the heart of this thesis project for surgical planning and AR/MR navigation.

Conventionally, segmentation was a manual, laborious and time-consuming process performed by radiologists or other specialists and subject to significant inter- and intra-observer variability. The utilisation of AI facilitates the automation or semi-automation of this process, thereby ensuring enhanced efficiency, consistency, and potential accuracy in the results obtained.

DL algorithms, and in particular Convolutional Neural Networks (CNN), have demonstrated exceptional performance in this field. Architectures such as U-Net and its many variants have become the gold standard for medical image segmentation, thanks to their encoder-decoder architecture with "skip connections" that allows contextual information at different scales to be combined [Marinakis et al., 2024, [11]]. The extant literature provides a substantial corpus of CNN-based approaches for lung nodule segmentation. For instance, Wang et al. (cited in Zhi et al., 2023 [12] have developed specialised architectures, such as

Central Focused Convolutional Neural Networks (CF-CNN), to specifically address the challenging segmentation of juxta-pleural nodules, which are located in close proximity to the chest wall. As posited by Singadkar et al. (cited in [12]), residual de-convolutional networks have been proposed as a means to enhance feature learning and contour accuracy.

These illustrations demonstrate the efficacy of CNNs in addressing specific challenges related to lung segmentation through targeted solutions, emphasising the versatility and potential of (DL) methodologies in medical imaging. More recently, the scientific community has shifted its focus to Transformer architectures, which have been shown to possess the capacity to model long-range dependencies within data, thereby overcoming one of the inherent limitations of CNNs, whose receptive fields are local by nature. In the field of nodule segmentation, hybrid CNN-Transformer architectures have been proposed, including DPBET (cited in Zhi et al., 2023 [12]), which integrates the advantages of both architectures: CNNs are utilised for the extraction of intricate local features, while transformer architectures are employed to capture global context and long-range relationships. This approach has been demonstrated to enhance the precision of nodule delineation, particularly in cases where the nodules exhibit complex geometries or are situated in challenging anatomical environments.

The most recent research endeavours have focused on the development of architectures based on State Space Models, such as Mamba, which aim to capture long-range dependencies with greater computational efficiency than Transformers. Systematic benchmark studies, such as the seminal one by Isensee et al. [13], have begun to compare these new architectures (e.g., U-Mamba) with established standards. However, these benchmarks have highlighted the superiority of the nnU-Net framework in terms of cross-fold accuracy and stability, a result of its robust ability to self-configure based on the specific characteristics of the dataset (resolution, anisotropy, etc.). CNN-based models, notably those implemented in the nnU-Net framework, have been shown to exhibit enhanced reliability in complex and real-world clinical contexts.

The development and validation of these models was facilitated by the availability of substantial, accurately annotated public datasets. Data collections such as LIDC-IDRI [Armato III et al., 2011, [6] and its derivative for the LUNA16 challenge [Setio et al., 2017, [7]] have been of seminal importance for the training and comparison of thousands of algorithms worldwide. Indeed, they have established benchmarks and driven innovation.

Despite the considerable progress that has been made, AI-based segmentation still faces several challenges, including the need for large amounts of annotated data, the generalisability of models to heterogeneous data, the segmentation of very small or low-contrast structures, and the interpretability of results.

However, the capacity of AI to generate detailed and accurate digital representations of patient anatomy establishes the basis for contemporary IGS and AR applications. The decision to employ TotalSegmentator [Wasserthal et al., 2023, [14]] in this thesis project was therefore a methodological decision that was carefully considered, based on evidence of its reliability, superior performance (as also demonstrated by comparisons with other nnU-Net models), and ease of integration, which characterise it as a state-of-the-art solution for this task.

2.4 HoloLens 2: features and medical applications

The Microsoft HoloLens 2 is one of the most advanced (HMD) devices for MR and AR applications in the medical field. Its sophisticated combination of hardware capabilities and an expanding software ecosystem enables it to overcome the limitations of traditional technologies, unlocking new possibilities for visualization, surgical planning, intraoperative navigation, and medical training [2] [4].

A key strength of the HoloLens 2 lies in its ability to project stable, high-resolution, and high-fidelity 3D holograms directly into the user's field of view. This enables immersive visualization of highly detailed patient-specific anatomical models generated from medical imaging data such as CT or MRI scans. The device's advanced optics and spatial sensors ensure realistic and precise hologram placement, critical for clinical accuracy and user confidence during surgical procedures.

The device integrates sophisticated hand tracking and voice recognition systems, allowing users to manipulate digital content without relying on external input devices such as mice or keyboards, which are impractical in sterile environments like operating rooms. Users can rotate, scale, and slice anatomical models through intuitive hand gestures, while voice commands provide hands-free control. This natural interaction paradigm not only improves operational efficiency but also enhances sterility and safety by minimizing physical contact with shared surfaces.

One of the most important features of the HoloLens 2 is its real-time spatial mapping capability. Equipped with depth sensors and cameras, the device continuously scans and understands the surrounding physical environment, allowing holograms to be anchored to fixed points in the real world. This spatial awareness is essential for AR navigation applications, where virtual models must be precisely aligned with the patient's anatomy or surgical field. Such alignment ensures that holographic overlays correspond accurately to physical structures, enabling safer and more precise interventions.

The HoloLens 2 stands out for its connectivity options and its ability to integrate with advanced medical software ecosystems. A prominent example is integration with 3D Slicer, a widely used platform for 3D medical image visualization and processing. Through communication protocols such as OpenIGTLink, the device can receive and transmit real-time data streams, facilitating dynamic updates of anatomical models during surgery. This bidirectional data exchange supports innovative workflows in AR-assisted surgery, allowing surgeons to view real-time, patient-specific data superimposed onto the operative field, thereby enhancing precision and intraoperative decision-making. Together, these features make the HoloLens 2 a highly versatile and powerful tool in medical practice. Its applications range from preoperative planning—where surgeons can study patient anatomy in an immersive 3D environment—to intraoperative guidance that enables more accurate navigation within the patient's body. Additionally, its ability to display interactive 3D models is invaluable for medical education and training, offering immersive and realistic experiences beyond conventional methods.

Furthermore, ongoing software developments and updates to the HoloLens platform, supported by a growing community of medical AR applications, promise to extend the device's capabilities even further. The integration of AI and machine learning algorithms may enhance real-time data interpretation and surgical decision support, making the HoloLens 2 an even more integral part of future surgical workflows.

Chapter 3

Materials and Methods

3.1 Tools used

3.1.1 CT Dataset

For testing the proposed system, the LIDC-IDRI dataset was used [6]. This is one of the most comprehensive public collections of thoracic CT images available for radiology and diagnostic research. The database contains 1018 CT scans acquired in different US clinical centres and annotated independently by four experienced radiologists, followed by a collective review phase. The annotations relate to the presence, location, size, and morphological characteristics of suspected lung nodules. Each CT scan is accompanied by XML files containing the radiologists' manual annotations, which include information on: suspected malignancy (scale from 1 to 5), margins, spiculations, and internal structure of the nodules.

Nodules are classified into three categories:

- Nodules ≥ 3 mm, fully segmented by each radiologist;
- Nodules < 3 mm, noted but not segmented;
- Non-nodular lesions, reported as non-clinically relevant observations.

Due to the richness and accuracy of its annotations, this dataset represents a fundamental resource for the development and validation of automatic segmentation and classification algorithms based on deep neural networks.

The LIDC-IDRI is publicly available via The Cancer Imaging Archive (TCIA) portal at the following address: `https://wiki.cancerimagingarchive.net/display/Public/LIDC-IDRI`.

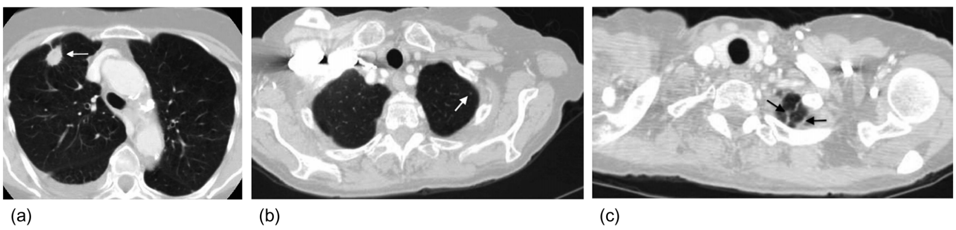


Figure 3.1: Examples of lesions considered to satisfy the LIDC/IDRI definition of (a) a nodule ≥ 3 mm, (b) a nodule < 3 mm, and (c) a non-nodule ≥ 3 mm [23].

3.1.2 3D Slicer

3D Slicer is an open-source platform for processing, visualising, and analysing medical images, widely used in medical research and clinical applications [15]. The software supports numerous medical image formats, including DICOM, NIfTI, and MetaImage, and allows the integration of custom modules via Python or C++. Its modular architecture allows for the expansion of functionality through extensions covering areas such as segmentation, registration, quantitative analysis, and AR [16].

In the context of this thesis, 3D Slicer was used as the main environment for loading, visualising, and processing thoracic CT images. It was used to segment anatomical structures and lung nodules, and to export segmented 3D models in STL format, which were then used for AR visualisation using Unity and HoloLens 2. The ability to use Python interactively through the internal console or via scripts facilitated the automation of the segmentation and post-processing procedures, reducing the time required for the entire workflow. Furthermore, 3D Slicer was also used to compute the optimal path for the biopsy needle, taking into account the anatomical constraints and minimising the risk of damaging surrounding critical structures.

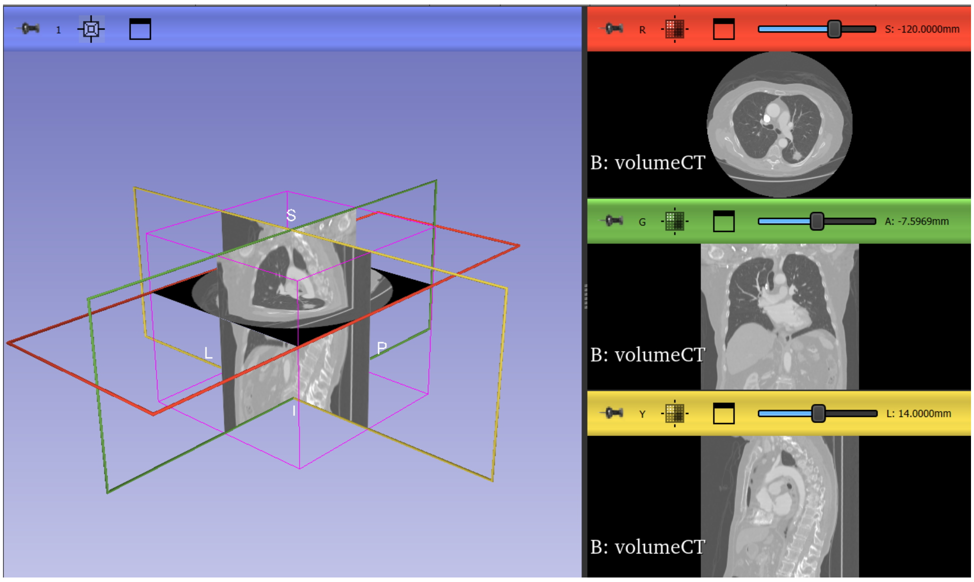


Figure 3.2: Standard 3D Slicer views for thoracic CT volume analysis: 3D view with slicing planes (left) and 2D axial, coronal, and sagittal views (right).

Specifically, different extension 3D Slicer's modules were used: Segment Editor [17], Total Segmentator [14], and Percutaneous Approach Analysis (PAA) [18], each of these plays a key role in the different stages of the process. The contributions of these modules are discussed in the following sections. 3D Slicer's highly interactive user interface also allowed immediate visual validation of the results, improving segmentation accuracy and workflow efficiency.

3.1.3 Unity and MRTK

Unity, a widely used cross-platform graphics engine for developing interactive 3D applications, particularly in the fields of (VR), (MR) and AR, was used to create the MR application [19]. Unity is a development environment that allows the management of 3D objects, animations and interactions via C# scripts, thus rendering it the ideal solution for integration with devices such as Microsoft HoloLens 2.

In particular, Unity has been adopted for importing and visualising segmented 3D models derived from chest CT scans, allowing interactive manipulation within the MR environment. Unity's XR plugin management system has been developed for the purpose of simplifying the process of supporting multiple extended reality (XR) platforms. This is realised through the provision of a unified interface for the management of different XR SDKs. This system facilitates the configuration and deployment of applications on various devices without the necessity of modifying the base code. OpenXR, a standard for VR and AR applications that is both open and royalty-free, ensures compatibility and interoperability between hardware and software by standardising APIs across all devices. This allows Unity applications to integrate seamlessly with Microsoft HoloLens 2 and other augmented and VR devices [20].

The scene developed in Unity included:

- Importing anatomical models in `.stl` format obtained from 3D Slicer.
- The configuration of a 3D space proportional to the real dimensions of the human body.
- Scripts in C# for dynamically loading models and implementing gesture interactions.
- Scene optimisation (light, depth, materials) for realistic rendering when superimposed on patients.

To further streamline user interaction and interface development, the Microsoft Mixed Reality Toolkit (MRTK) [21] was integrated into the project. MRTK is an open source collection of components and tools for Unity, designed to facilitate the development of MR applications on devices such as HoloLens 2.

MRTK played a central role in the project by:

- Enabling direct manipulation of 3D models through natural interactions (two-handed manipulation, pinch-to-zoom, rotation).
- Adding 3D UI elements that float in space (e.g., drop-down menus, interactive labels).
- Ensuring spatial stability with spatial anchors that keep models aligned to the patient's body.
- Integrating voice input and eye tracking systems, useful in surgical environments where touch interaction is not possible.

Figure 3.3: Microsoft Mixed Reality Toolkit (MRTK) demonstration scene [21].

The synergy between Unity and MRTK has resulted in an AR application that supports immersive and interactive visualisation of anatomical data, facilitating preoperative planning and improving spatial understanding of thoracic structures. The versions used in this project were Unity 2021.3.19f LTS and MRTK 2.8.3, both selected for their stability and full compatibility with Microsoft HoloLens 2.

3.1.4 HoloLens 2

In this thesis project, Microsoft HoloLens 2 device was used for the immersive and interactive visualisation of 3D models derived from CT scans of the patient. HoloLens 2 is an MR viewer that allows digital content to be superimposed on the physical environment while maintaining the user's spatial awareness. Compared to the first generation of the device, the second version introduces significant improvements such as an expanded field of view, eye tracking, a more accurate gesture recognition system, and improved ergonomics [22], features that make it particularly suitable for clinical and pre-operative planning.

The visor integrates an advanced set of sensors, including an RGB camera, depth sensors, an Inertial Measurement Unit (IMU), microphones, and a dedicated Holographic Processing Unit (HPU), which enables real-time rendering of virtual objects perfectly aligned with the user's physical space. Such features favour its application in high-tech clinical fields such as thoracic surgery and interventional oncology, where the 3D representation of anatomical and pathological structures can improve the accuracy of surgical planning and the surgeon's spatial perception [1][2].

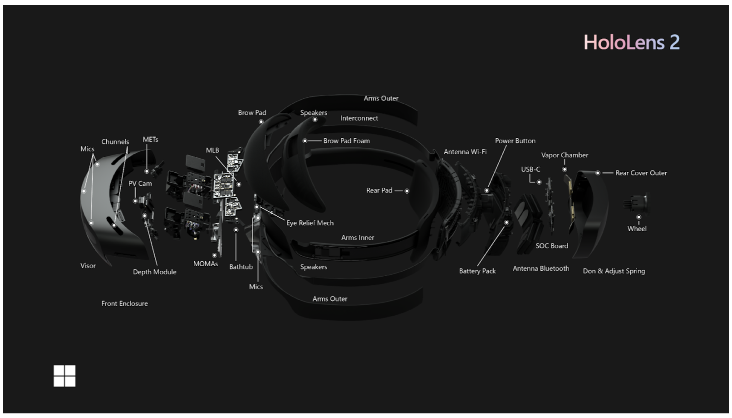


Figure 3.4: Exploded view of the Microsoft HoloLens 2, detailing its internal components [22].

The Unity graphics engine was used to integrate the 3D models into the visor, taking advantage of its compatibility with the XR SDK and the MRTK.

The segmented models obtained from the CT images were exported into Unity-compatible formats such as .glb and .fbx. These models were then imported into the Unity development environment for further processing and interaction design.Subsequently, the completed Unity project was built and deployed as a Universal Windows Platform (UWP) application [23].

UWP is a Microsoft development platform that enables applications to run natively on a wide range of Windows devices, including the HoloLens 2. By targeting UWP, the application can fully leverage the hardware and system capabilities of HoloLens 2, such as spatial mapping, gesture recognition, and optimized performance.

The dynamic integration between HoloLens 2 and 3D Slicer was achieved using the OpenIGTLink protocol, an open and modular standard designed to support real-time communication between software and hardware devices in the context of image-guided therapy (IGT) [24].

Originally developed at Brigham and Women's Hospital and MIT, OpenIGTLink enables the bi-directional transfer of data such as medical images, spatial transformations (4x4 matrices), tracking signals, device states, while ensuring low latency and high time synchronisation, which are key features for intraoperative applications. In this project, OpenIGTLink served as the core communication bridge between 3D Slicer and Unity, used for CT data processing and anatomical model preparation, and the Unity-based application on HoloLens 2. The SlicerIGT extension in 3D Slicer facilitated TCP/IP communication with external clients.

A key functionality implemented in this work was the real-time visualization of CT slices projected through the segmented 3D anatomical model. As the user interacted with the model in MR, the corresponding CT slice was dynamically streamed from 3D Slicer and overlaid in its correct spatial position within the 3D environment on HoloLens 2. This provided an intuitive method for exploring internal structures and improved spatial understanding of the patient's anatomy. Additionally, OpenIGTLink was used to transmit:

- Spatial transformation matrices to maintain accurate registration between virtual and physical space.
- Segmented surface meshes (e.g., STL or OBJ formats), rendered in Unity for MR visualization.
- Live updates to segmentation data or model positioning, allowing seamless synchronisation between the surgical planning environment and the AR display.

On the Unity side, a custom C# script handled socket communication, interpreted OpenIGTLink message headers, and reconstructed the transmitted content for MR rendering. This interactive pipeline ensured robust, real-time synchronisation between 3D Slicer and the HoloLens 2 viewer, supporting the immersive visualization of anatomical data.

The adoption of OpenIGTLink provided a flexible and scalable infrastructure, not only for the current application but also for future extensions, such as integration with optical or electromagnetic tracking systems, intraoperative sensors, or robotic devices for advanced image-guided surgical procedures [13].

3.2 Segmentation of lung nodules and thoracic structures

The segmentation of thoracic anatomical structures was automated, with TotalSegmentator [14] - an advanced implementation of the nnU-Net architecture (no-new-U-Net) [13] - being utilised for this purpose, representing the current state-of-the-art for 3D medical image segmentation. The segmentation process is centred on critical structures that are essential for the planning of biopsies, including lung nodules, bronchial trees, and major vasculature. The objective of this segmentation is to generate precise 3D anatomical reconstructions for the purpose of preoperative biopsy planning. This approach has been demonstrated to optimise needle trajectory, minimise the occurrence of complications (e.g. pneumothorax or haemorrhage) and improve the accuracy of sampling.

3.2.1 Architecture and training dataset

TotalSegmentator uses a self-configuring 3D U-Net model that automatically adapts all training parameters according to the characteristics of the dataset (e.g., spatial resolution, number of classes, volume size). The model was trained on a clinical dataset consisting of 1204 CT scans from patients with heterogeneous clinical conditions, including different scanner types, contrast protocols, thoracic and abdominal pathologies, and age groups. The diversity of the dataset, including more than 16 scanners and 8 different clinical centers, ensured remarkable robustness and generalizability of the model.

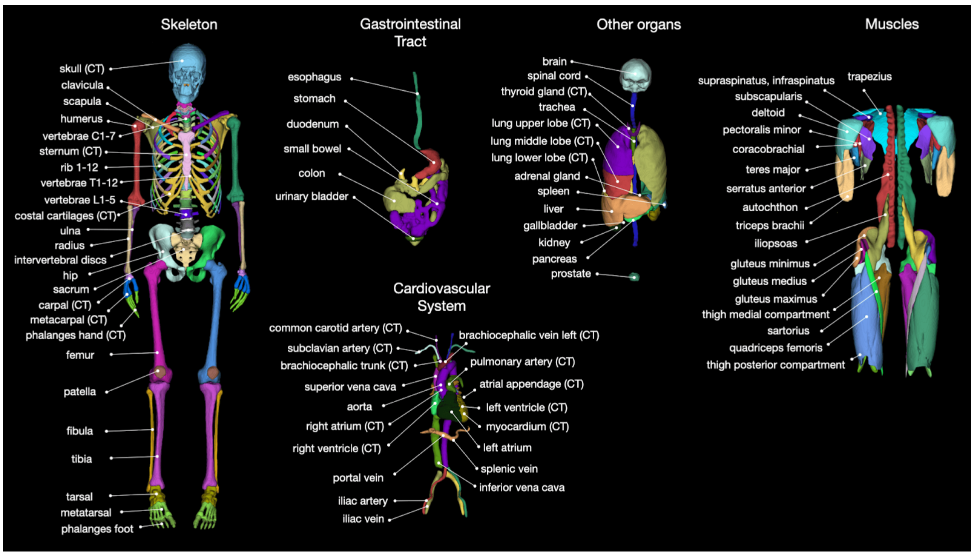


Figure 3.5: Visualization of the 104 anatomical structures segmented via TotalSegmentator.

A total of 104 anatomical structures (Figure 3.5) were segmented, including: lungs (divided into lobes), bronchi, trachea, heart, thoracic and abdominal aorta, iliac veins, vertebrae, ribs, diaphragm, and paravertebral muscles.

3.2.2 Preprocessing, resolution and inference

Images were resampled at 1.5 mm isotropic resolution for training the main model. A 3-mm version was created for clinical settings with low computational capacity. During inference, the model takes approximately 2-3 minutes to fully segment on an Nvidia RTX 3090 GPU [14]. The segmented volumes were subsequently converted into 3D meshes and integrated into the Unity environment for visualization with AR devices (HoloLens 2).

3.2.3 Evaluation Metrics

The assessment of the model's performance was conducted by means of the application of two standard metrics:

- **Dice Similarity Coefficient (DSC)**: measuring volumetric overlap between predictions and ground truth;
- **Normalized Surface Distance (NSD)**: evaluating surface alignment within a 3 mm tolerance.

The high-resolution model obtained a mean DSC of 0.943 and an NSD of 0.966, indicating excellent segmentation performance, even when confronted with pathological variations such as tumours, bone fractures, hernias, and previous surgical modifications.

When compared to a nnU-Net trained on the BTCV dataset, TotalSegmentator achieved significantly superior results (DSC: 0.932 vs. 0.871, $p < 0.001$) [14].

3.2.4 Comparison with other segmentation models

According to the systematic benchmark performed by Isensee et al. [13], the nnU-Net architecture remains superior to models based on Transformer (e.g., SwinUNETR, nnFormer) and Mamba layers (e.g., U-Mamba), both in terms of accuracy and cross-fold stability. CNN-based models, especially those implemented in the nnU-Net framework, are more reliable even in complex clinical environments. Due to its reliability, performance, and ease of integration, TotalSegmentator was chosen as the segmentation solution for this project.

3.2.5 Clinical integration and use in the project

In the context of the present work, segmented anatomical structures - particularly the bronchi, thoracic aorta, and pulmonary nodules - were used to create accurate 3D representations of the thoracic cavity.

These were integrated into an immersive AR system to support preoperative planning. Through real-time visualisation on the HoloLens 2, clinicians can explore the spatial relationships between nodules and surrounding structures, aiding in the simulation and selection of the optimal needle insertion trajectory for lung biopsy procedures.

One of the aspects that makes TotalSegmentator particularly advantageous for this project is its nature as a native extension of 3D Slicer.This means that the tool fits seamlessly into the software environment we already use, without forcing us to take cumbersome steps or seek external programming expertise.

The complete process, from the generation of segmentations to the exportation of 3D models for visualisation within Unity, can be overseen directly from Slicer. The capacity to function within a unified environment facilitates a more intuitive process, renders it readily replicable, and enables adaptation to clinical requirements. This establishes the basis for a surgical planning workflow that can be effectively implemented in clinical practice.

3.3 Optimal path planning for biopsy procedures

In the context of percutaneous procedures such as biopsies or ablative treatments, it is critical to define safe trajectories for needle placement that allow the target (a nodule or tumor) to be reached while avoiding sensitive anatomical structures such as blood vessels, bone, or other vital organs.

An extension of the 3D Slicer platform, the PAA module [18], addresses this need through interactive analysis and visualization of optimal trajectories. Using 3D anatomical models derived from medical images, the module calculates safe trajectories to reach the target point from the patient's skin surface while avoiding collisions with relevant anatomical structures.

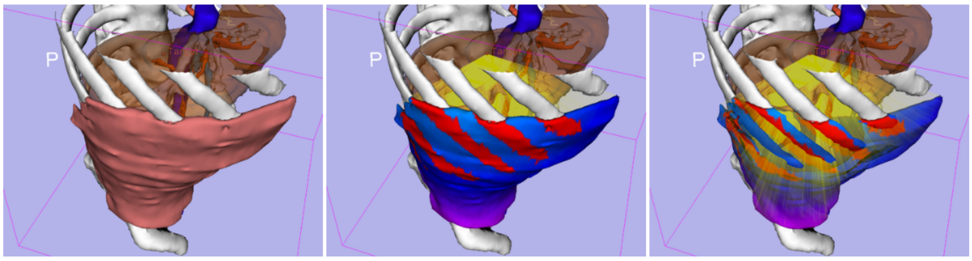


Figure 3.6: Illustration of PAA output for trajectory planning [18].

3.3.1 Data Structure and Input Parameters for PAA

The PAA module is based on the use of three fundamental 3D models, necessary for the definition and evaluation of needle insertion trajectories:

- Target point: a target point representing the position of the pulmonary nodule or lesion to be reached. This is defined manually by the operator in the 'Markups' module of 3D Slicer [25], after the nodule segmentation process (as described in Section 3.2), by visually placing the point on the CT scan (Figure 3.7). This approach allows greater flexibility in precisely locating the point of clinical interest.

- Skin model: As demonstrated in Section 3.2, the 3D representation of the patient's skin surface was obtained from the skin segmentation provided by TotalSegmentator. Initially, a solid structure is created; however, this segment is subsequently transformed into a hollow structure through the Segment Editor module [17] using the 'Hollow' effect. This step generates a 3D shell of uniform thickness from the outer contour of the original segment (Figure 3.8). The resulting model is then exported as a Model node, which is required for input into the PAA module.
  The Skin Model is primarily used to identify potential entry points for percutaneous procedures on the body surface. The main objective is to provide an accurate, clean reference surface for calculating initial needle insertion points.

- Obstacle model: includes all critical anatomical structures to be avoided, such as bones, vital organs, and blood vessels.In order to construct the model, the relevant

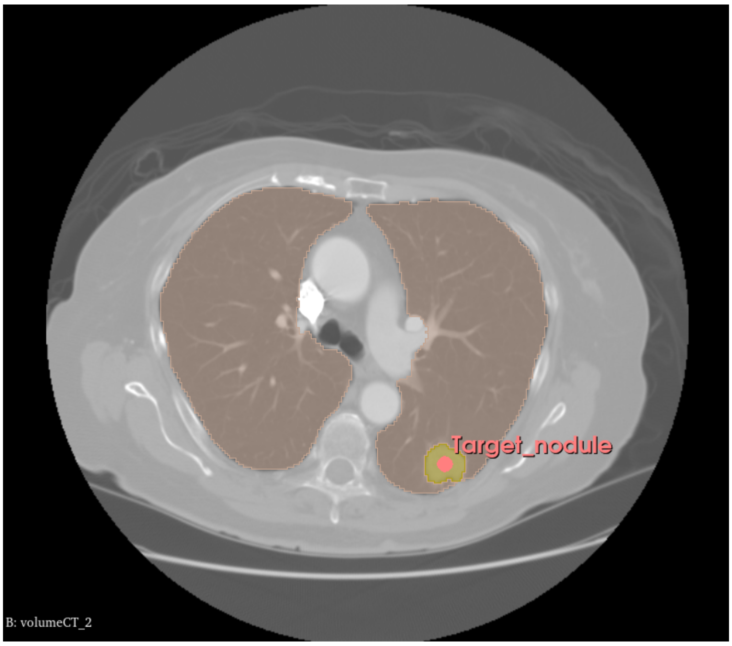


Figure 3.7: Axial CT view in 3D Slicer showing the manually defined "Target_nodule".

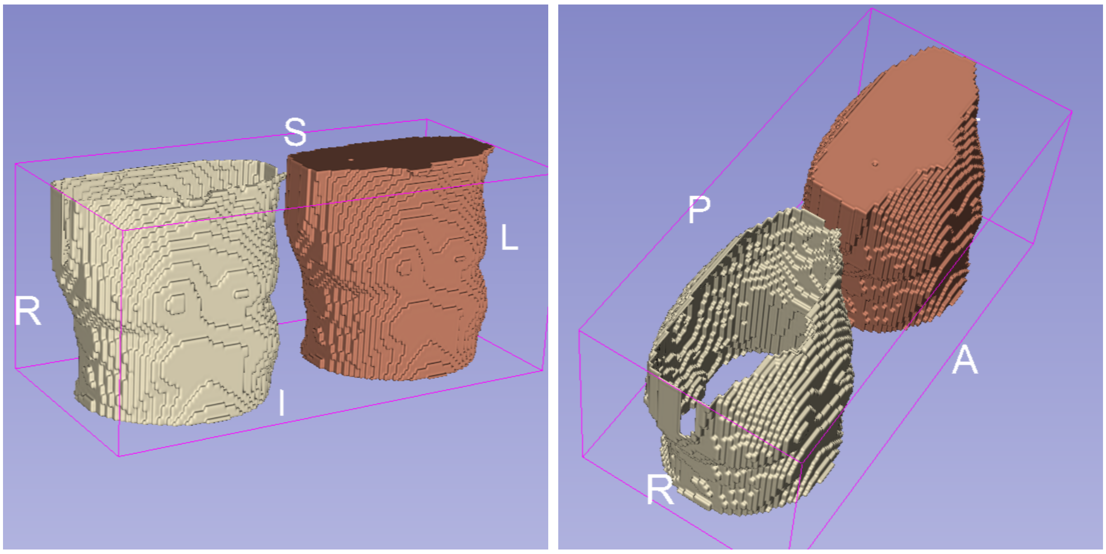


Figure 3.8: 3D Skin model. (Left) Processed view, potentially the 'hollow' shell, used to define needle entry points. (Right) Segmented surface.

anatomical segmentations generated by TotalSegmentator (as described in Section 3.2) were first selected and then merged into a single block using the logical union operator ("Add") of the Segment Editor [17]. This operation establishes a single, substantial segmentation that encompasses the entirety of the volume to be excluded in the trajectory calculation. Ultimately, the unified model was exported as a 3D model and optimised with a view to enhancing its management and computational efficiency.

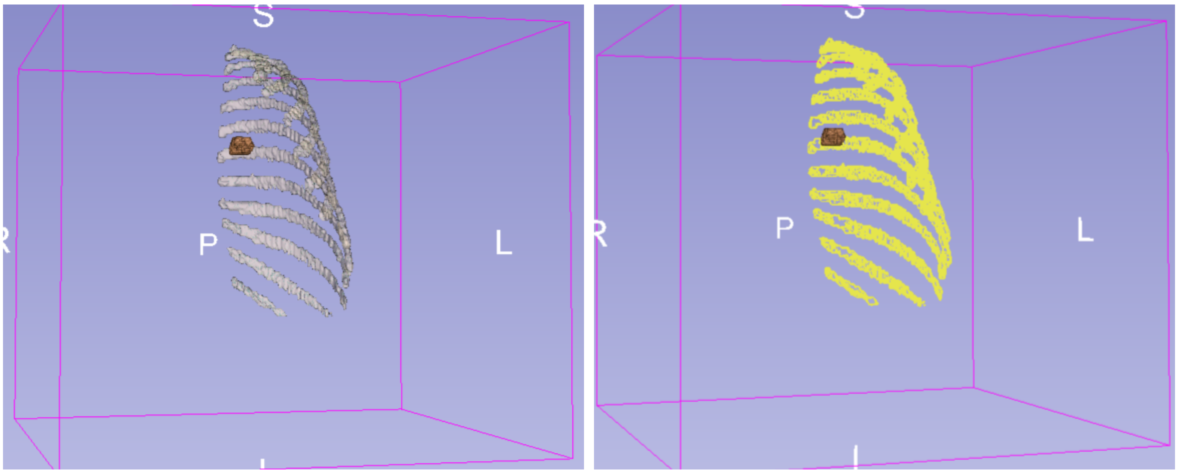


Figure 3.9: Example of a 3D obstacle model (rib cage). (Left) Initial merged bone segmentation. (Right) The model with geometric optimization.

Geometric optimisation techniques have been applied to optimise the Obstacle Model for real-time use and interactive visualization, and to reduce the computational complexity of the mesh. These operations are essential because the combination of multiple anatomical structures often results in dense and heavy models, which can hinder performance. An example of these optimisation operations is shown in Figure 3.9. The main post-processing operations include:

- Decimation: This technique, performed using the Surface Toolbox module of 3D Slicer [26], reduces the number of triangles that compose the mesh while maintaining the structure's overall shape. The level of reduction is controlled by a parameter called 'Target Reduction', which indicates the percentage of triangles to be eliminated (e.g., a value of 0.5 corresponds to a 50 % reduction).
- Extract edges: This function, available in the Models or Surface Toolbox modules, extracts only the visible contours of the mesh to create a simplified representation that highlights the main edges. This operation is useful for light visualisations and qualitative analyses, as well as for morphological comparisons between different segmentations.

The use of these techniques enables 3D Slicer to create models that are simpler and easier to manage, and they improve performance during processing and visualization while maintaining the essential details needed for clinical analysis.

3.3.2 Trajectory calculation algorithm

For each vertex of the skin model, a line segment is generated connecting the skin point to the target point. Each segment is checked for geometric feasibility:

- Collision checking: the module uses an algorithm based on Bounding Volume Hierarchy, implemented by a Binary Space Partitioning Tree (BSP Tree) structure, to efficiently test whether the trajectory intersects the obstacle model. The intersections are computed using VTK's vtkModifiedBSPTree.IntersectWithLine() functions [27].

- Path classification: if a trajectory intersects the obstacle, it is discarded, otherwise it is recorded as valid. The system keeps all acceptable trajectories in memory in the form of [targetPoint, skinPoint] pairs.

- Metric evaluation: for each valid trajectory, the Euclidean distance between the two endpoints is computed, defined as $d = \|P_{\text{target}} - P_{\text{skin}}\|$. The module automatically identifies the shortest and longest trajectories, providing a reference range for visual and clinical analysis.

- Accessibility map: to improve clinical interpretation, a colorimetric map of the skin is constructed. Each triangle in the skin mesh is assigned a score that takes into account the distance to the target and the geometric possibility of access. The result is a scalar field called Accessibility, which is displayed with a continuous colour map that distinguishes accessible from inaccessible skin areas (Figure 3.10).

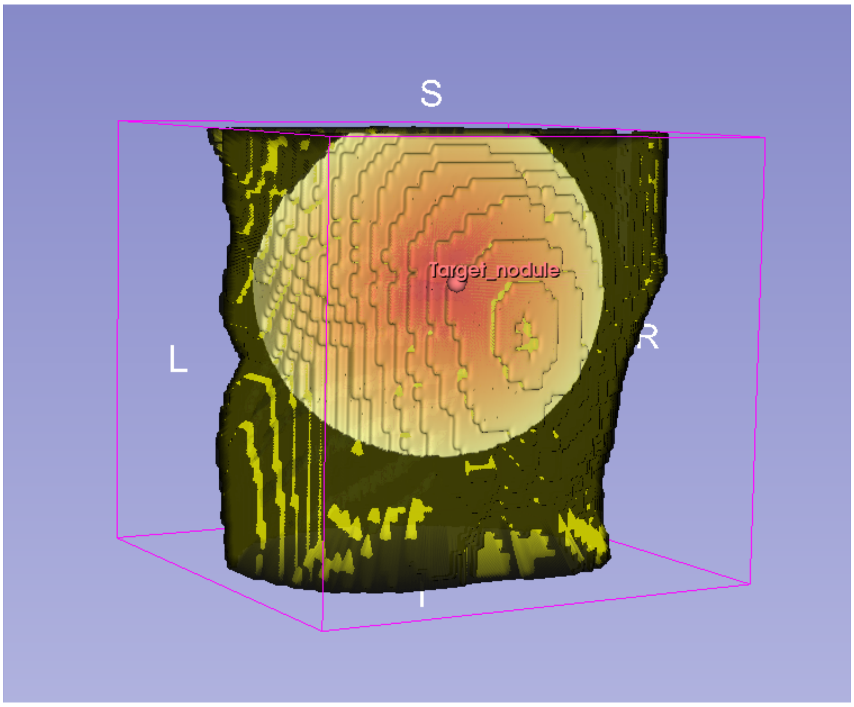


Figure 3.10: Accessibility map on the skin surface generated by PAA.

- Quantification of Accessibility: The algorithm calculates the Accessibility Score, defined as the sum of the areas of accessible triangles, weighted by distance and normalised to the total area of the skin model. This score provides a summary measure of the geometric accessibility of the target.

3.3.3 Interaction and visualisation

The interactive exploration of the computed needle trajectories is an integral part of the PAA module. Once the analysis has been performed, all possible paths from the skin surface to the target point are displayed in the 3D scene using clear colour coding: yellow for all valid paths, blue for the shortest path, green for the longest path, and red for the currently selected trajectory.

Users can explore these candidate paths interactively using numeric input or a slider interface. Once a trajectory has been selected, it can be extended or shortened along its longitudinal axis. This dynamic adjustment enables precise control over the location of the skin entry point, which is updated in real time and displayed as a marker on the patient's skin.

In addition to visual inspection, the module automatically computes the length of each path, providing a quantitative measure to inform decision-making. Once a clinically acceptable trajectory has been identified, the user can confirm and save the corresponding skin entry point by adding it to a Markup Fiducial List. This list can then be used seamlessly in downstream modules, such as PortPlacement, as discussed in the following section, for simulation and validation.

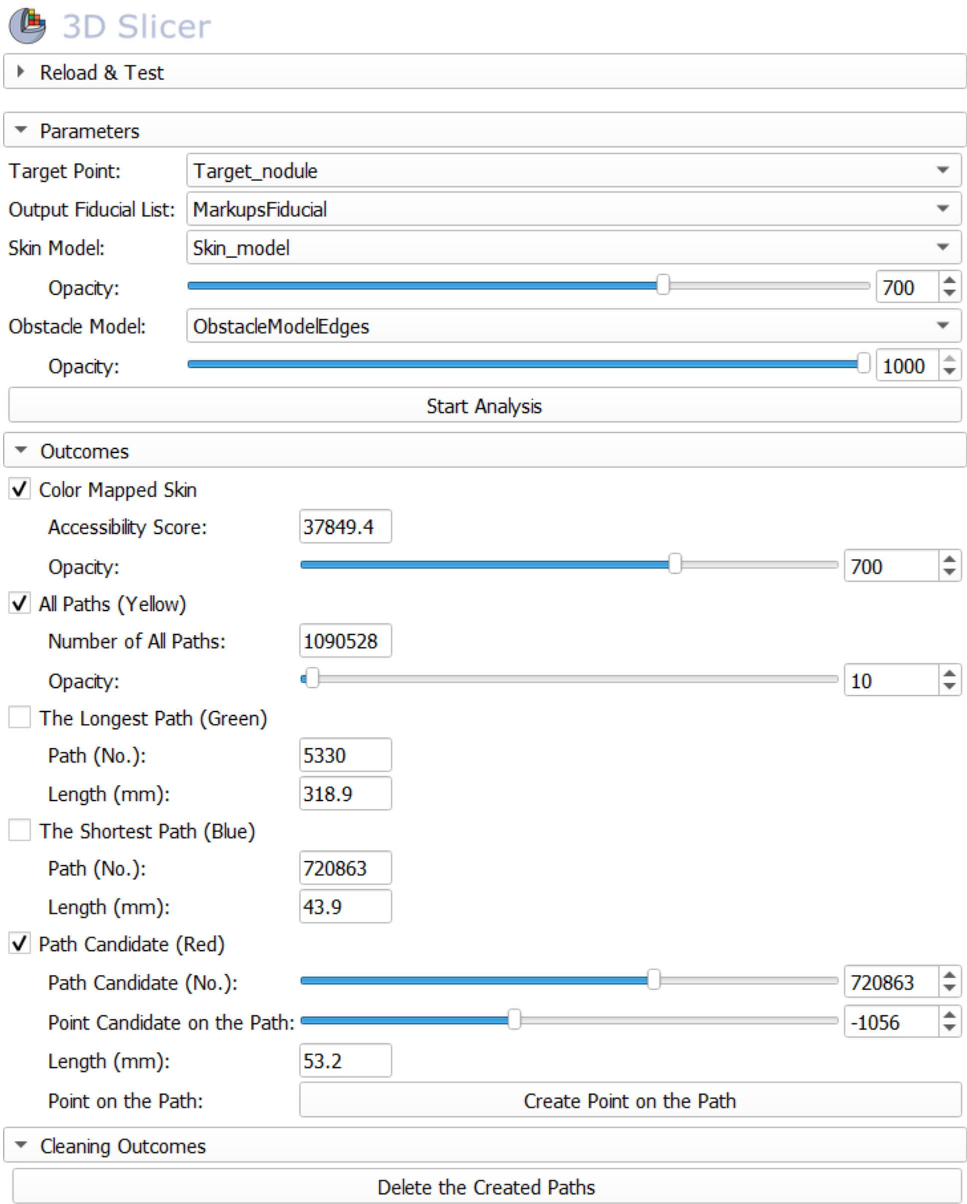


Figure 3.11: 3D Slicer GUI for the PAA module.

The graphical interface of the PAA module, including trajectory visualization and interactive controls, is shown in Figure 3.11.

3.3.4 Integration with the PortPlacement module for instrument simulation

The ideal trajectory and skin entry point are first defined using the PAA module. The PortPlacement module [28] is then employed to accurately simulate the insertion of the surgical instrument (e.g., a biopsy needle).

The surgical target set in the PortPlacement module corresponds exactly to the target point identified by the PAA module. Similarly, the skin entry point is used as the port position, i.e., where the instrument insertion is simulated.

The virtual instrument, which is represented by a configurable-dimensioned cylinder, is positioned at the skin entry point and oriented towards the target through the use of PortPlacement. This facilitates the visual and geometrical verification of the planned trajectory, ensuring that needle insertion respects anatomical constraints without unwanted collisions. This simulation allows the instrument's position and orientation to be rotated, translated, and adapted, optimising the trajectory according to the patient's actual shape and position.

3.4 Integration in Unity and visualization with HoloLens2

3.4.1 System architecture

This project, developed in Unity to enable visualisation and interaction with 3D anatomical models using Microsoft HoloLens 2, is based on the architecture presented in the study by Alicia Pose-Díez-de-la-Lastra et al. (2023)[2] (Figure 3.12). This study proposes a real-time integration system between HoloLens 2 and 3D Slicer, originally designed for planning the placement of pedicle screws. This reference project formed the basis for reusing the Unity scene and adapting the script structure to meet the specific requirements of our use case. In this context, the use case was surgical planning in the thoracic area, with particular reference to the localisation and visualisation of pulmonary nodules with subsequent needle insertion for biopsy.

Both the graphical interface and the management of segmented models were adapted, while the functional core of real-time communication between Unity and 3D Slicer was preserved.

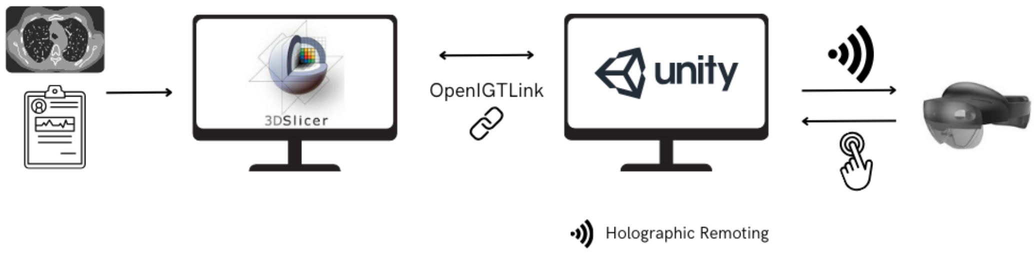


Figure 3.12: System architecture: HoloLens 2 connects to a Unity client via Holographic Remoting, which communicates with a 3D Slicer server using OpenIGTLink for image and transform data exchange.

As described in Section 3.1.3, Unity 2021.3.19f1 was used for mixed reality management. The `XR Plugin Management` module was configured for the `Windows XR Plugin`. This configuration allows applications compatible with the HoloLens 2 headset to be developed in the `UWP` format.

The `DefaultHoloLens2ConfigurationProfile`, which is the default profile provided by MRTK v2.8.3, was selected. This profile automatically enables the main subsystems required for proper interaction with Microsoft devices.

These subsystems include:

- Hand tracking: for hand recognition and tracking.
- Spatial mapping: for understanding the surrounding environment.
- Scene understanding: which identifies planes and surfaces.
- Voice commands: for voice interaction.

3.4.2 Importing and rendering 3D models

The anatomical models exported by 3D Slicer as meshes (mostly in .obj format) are imported into Unity as static GameObjects. To improve visual integration with the real environment, an MRTK/Standard shader-based translucent material with active alpha blending is applied [21]. This approach achieves the following:

- Soft transparencies are useful for observing internal structures without completely obstructing the view of the underlying anatomy.
- A visually 'light' appearance, which is suitable for the clinical environment and does not obstruct the operator's view.
- Perfect integration with the surrounding real environment — a fundamental feature for AR applications.

Since Unity uses a left-handed Y-up coordinate system and 3D Slicer uses the RAS (right-anterior-superior) system, customised coordinate transformations had to be implemented to ensure correct spatial alignment. The applied transformations include:

- 180° Y-axis rotation for left-right alignment,
- Z-axis inversion for correct front-rear orientation,
- Maintaining the Y-axis for upper-lower alignment.

This process is critical for ensuring accurate registration between the 3D model and the patient's body during AR visualisation, which is essential for the application to be clinically effective.

3.4.3 User interface and interactions

The user interface was created using MRTK prefabs, which are optimised for mixed reality components and support natural, non-contact interactions - making them ideal for surgical environments, where hygiene and sterility are of the utmost importance.

The main components used are:

- PressableButtonHoloLens2: buttons that are sensitive to touches, gestures, or voice commands and are optimised for remote interaction.
- BoundingBox: manipulation of models (translation, scaling, and rotation) via natural gestures using one or two hands.
- Tooltip, Slate, and SolverHandler: these display contextual information windows and fix UI elements in space, adapting them dynamically to the environment.

3.5 LungNoduleBiopsyPlanner module in 3D Slicer

3.5.1 LungNoduleBiopsyPlanner module in 3D Slicer

The LungNoduleBiopsyPlanner, a 3D Slicer extension, aids clinicians in preoperative planning for percutaneous lung biopsies. It processes CT scans to create 3D anatomical models and calculates safe needle trajectories to target nodules, generating data exportable for AR-guided surgical navigation. This Slicer-based development aligns with the increasing synergy between planning software and AR devices like Microsoft HoloLens 2, drawing inspiration from the data preparation and communication needs inherent in integrated systems, such as the HoloLens 2 and 3D Slicer integration for pedicle screw planning demonstrated by Pose-Díez-de-la-Lastra et al. (2023) [2].

The LungNoduleBiopsyPlanner module adapts these principles for use in lung biopsy procedures, combining and optimising the functionalities of separate modules such as PercutaneousApproachAnalysis [18] and PortPlacement [28] into a single, integrated workflow.

The module's architecture follows the Model-View-Controller (MVC) pattern, which is an established practice in the development of interactive applications, particularly 3D Slicer extensions [29].

The view is the graphical user interface (GUI), through which the operator interacts with the system.

The Controller, implemented by the LungNoduleBiopsyPlannerWidget class, handles user input from the GUI and invokes the appropriate operations, updating the view accordingly.

The model consists of two main elements:

- The LungNoduleBiopsyPlannerLogic class encapsulates the logic and algorithms for image processing and path calculation.
- The ParameterNode is a Slicer-specific object that stores the current state of the module and data references (volumes, models and fiducials), as well as user-set parameters. This ensures data persistence between work sessions and interface consistency.

Chapter 4

Results

4.1 Evaluation of segmentations

The accuracy of the 3D anatomical models used in the AR application is critically dependent on the quality of the initial segmentation of thoracic structures from CT scans. As described in section 3.1, for this project, automated segmentation was performed using TotalSegmentator. The primary structures of interest for lung biopsy planning, including lung nodules, the bronchial tree, major vasculature, ribs, and lungs, were segmented to generate the 3D reconstructions for preoperative planning.

The published performance for the TotalSegmentator model trained on CT images with a 1.5 mm slice thickness (high-resolution) reports a mean (DSC) of 0.943 (95% CI [0.938, 0.947]) and a mean (NSD) of 0.966 (95% CI [0.962, 0.971]). These values indicate remarkable volumetric overlap and precise surface alignment of the segmented structures against the ground truth annotations [5]. For clinical settings with lower computational resources, a version of the model trained with 3 mm slice thickness images (low-resolution) was also developed and evaluated. This version exhibited a mean DSC of 0.840 (95% CI [0.836, 0.844]), which was, as expected, lower than that of the high-resolution model. However, it is important to note that the NSD score remained comparably high at 0.966 (95% CI [0.962, 0.969]). This suggests that while the lower resolution introduces slight imprecision at the structure borders, the 3 mm segmentation results remain substantially correct and clinically useful, especially considering the 3 mm tolerance inherent in the NSD metric.

The robustness of TotalSegmentator is further confirmed by its ability to generalize to external datasets (such as BTCV, from a different geographical and acquisition context) and its consistent performance even in the presence of significant pathological variations.

In terms of efficiency, the inference time for a complete segmentation of a medium-sized thoraco-abdominal study (512x512x458 voxel matrix) is approximately 2 minutes and 49 seconds for the high-resolution (1.5 mm) model and about 53 seconds for the low-resolution (3 mm) model, using an Nvidia GeForce RTX 3090 GPU [5]. Both timings are considered fully compatible with preoperative planning workflows.

Beyond the published metrics, a qualitative assessment of the segmentations produced by TotalSegmentator was conducted on the CT datasets utilized for this thesis project.

This assessment focused on the suitability of the generated 3D models for AR-assisted lung biopsy planning:

- Lung nodules: The delineation of lung nodules was generally precise, providing a reliable target for biopsy planning (Figure 4.1).

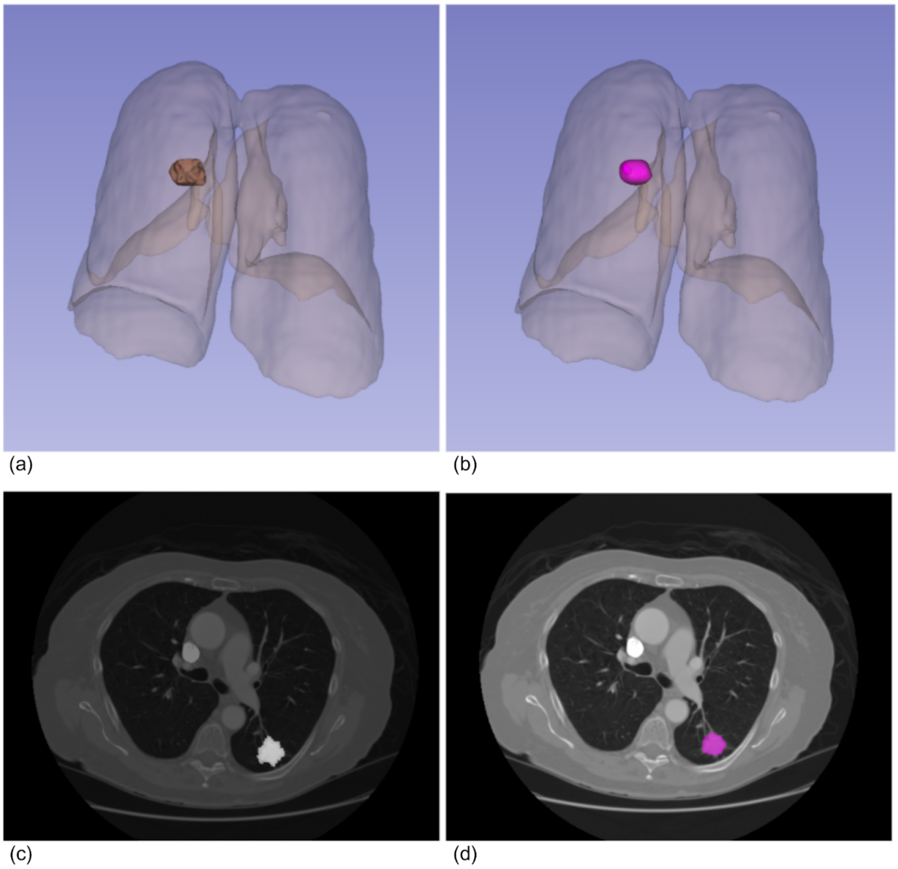


Figure 4.1: Example of lung nodule segmentation using TotalSegmentator (a) 3D lung model with the manually annotated nodule (brown). (b) The same 3D lung model with the nodule segmented by TotalSegmentator (pink). (c) Axial CT slice showing the lung nodule manually annotated. (d)The same CT slice with the segmentation mask generated by TotalSegmentator overlaid on the nodule (pink).

- Bronchial tree and vasculature: The accurate segmentation of major airways and vessels was a prerequisite for the planning of needle trajectories that minimise the risk of complications such as pneumothorax or haemorrhage.

- Rib cage and lungs: Segmentation of the rib cage and lung parenchyma provided the necessary anatomical context and obstacle definition for path planning.

Although rare failure cases have been documented, primarily on very small structures or in particularly complex anatomical contexts leading to merging or missed small portions, the overall reliability, high metric performance (especially of the 1.5 mm model), and ease of native integration within 3D Slicer (as an installable extension) made TotalSegmentator the optimal segmentation solution for this thesis project. The results generated by it thus form the accurate and reproducible basis for the subsequent processing and visualization of anatomical models in the developed AR system.

4.2 Assessment of the Unity-based AR application for HoloLens 2

Implementation of the Unity scena

At the start of the developed scene, the virtual environment is populated automatically with 3D models derived from patient imaging (Section 3.1.1): a skin surface model, a segmented lung model, and lung nodules identified in the segmentation phase (Section 3.2) (Figure 4.2). These models are initially aligned with each other and organised within a logical, hierarchical structure (e.g., the lungs are organised as children of the skin model and the nodules are organised as children of the lungs). This ensures consistency in joint manipulations and movements. This organisation facilitates the management of coordinated transformations and maintains the correct anatomical relationships during interactions.

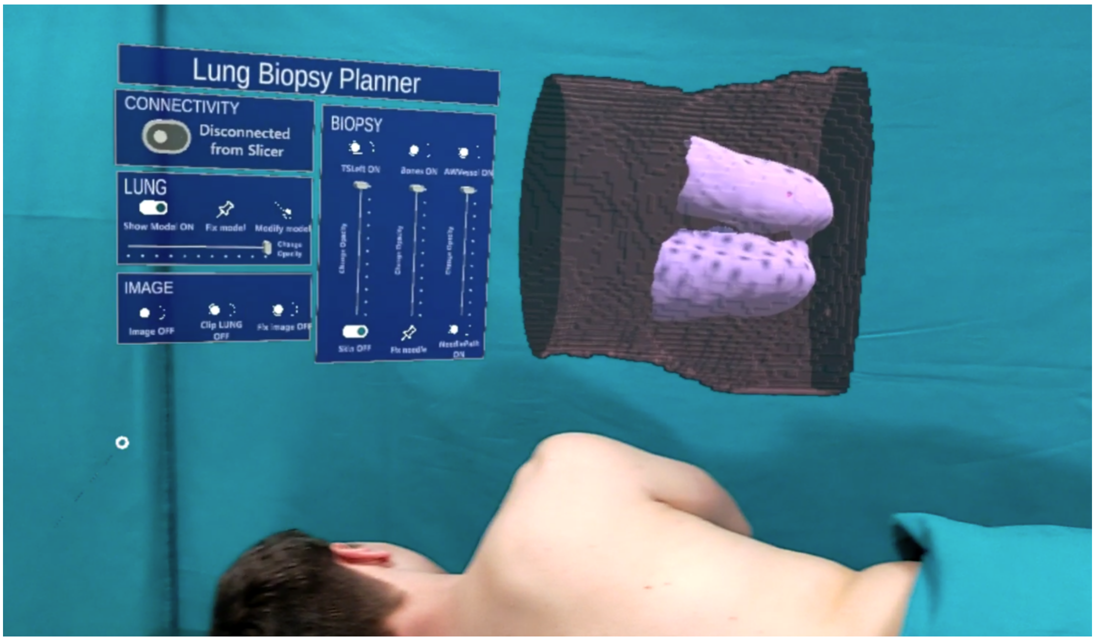


Figure 4.2: Initial scene setup in the HoloLens 2 AR environment.

Graphical menu interface and main components

Figure 4.2 shows an interactive menu developed with MRTK components that appears while the models are loading, floating in space, and anchored to the scene. This menu provides access to a range of useful functions during the surgical planning phase.

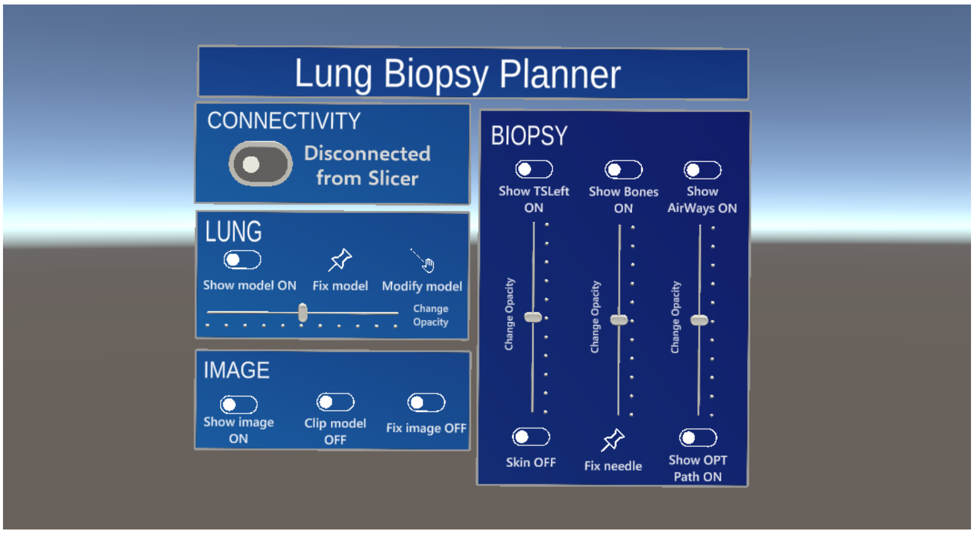


Figure 4.3: Interactive menu in the Hololens 2 AR environment.

4.2.1 Connection with 3D Slicer via OpenIGTLink

A dedicated toggle enables direct connection to 3D Slicer using the OpenIGTLink protocol. Once the connection is established, two image planes are generated in the scene, as shown in Figure 4.4.

- a fixed plane positioned above the anatomical models showing a fixed axial (or sagittal/coronal) section of the CT scan.
- a moving plane that the user can freely move and orient via a 3D handler, allowing them to visually scroll through the patient's CT scan.

Both planes are updated synchronously with CT slices from Slicer, enabling dynamic navigation of the volume directly above the anatomical model.

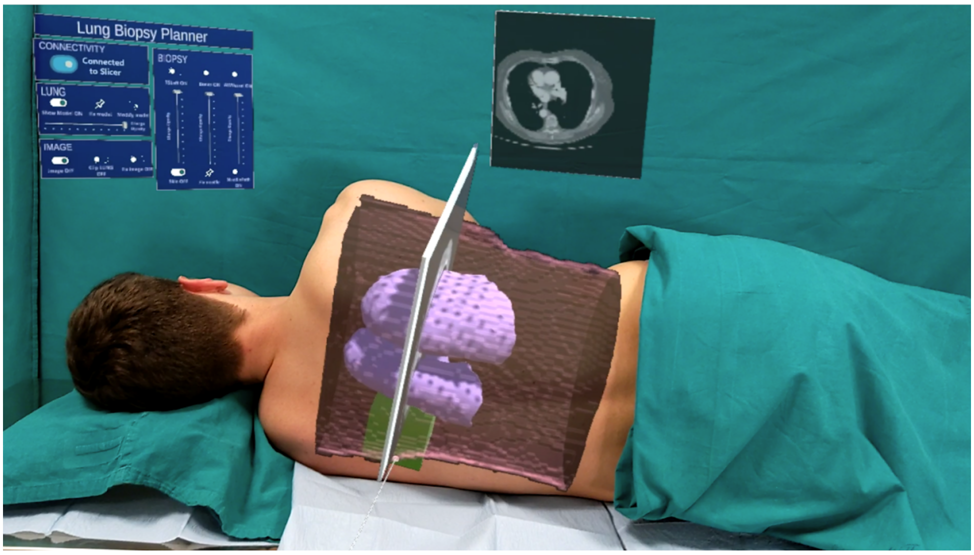
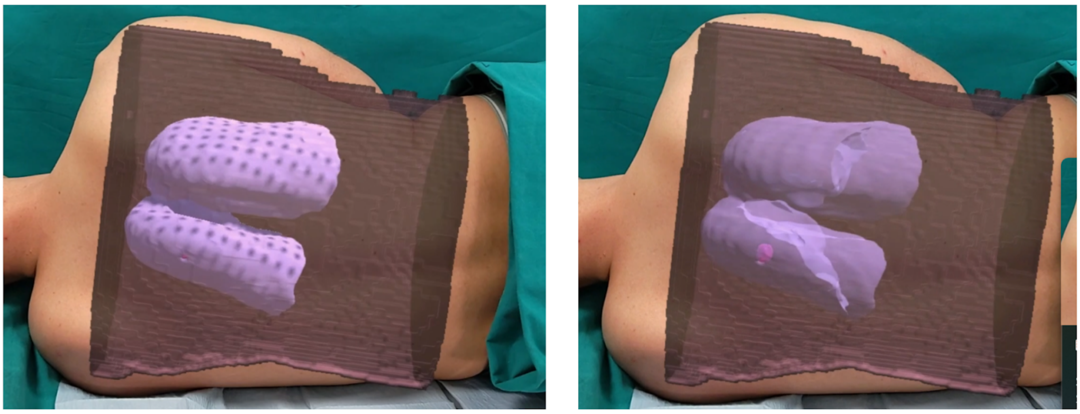


Figure 4.4: HoloLens 2 AR view with 3D Slicer integration via OpenIGTLink. The "Lung Biopsy Planner" UI (top left) shows an active connection to 3D Slicer. A fixed axial CT slice (top right) and a user-movable intersecting CT slice (center, with green handler) are streamed from Slicer for dynamic volumetric navigation.

Lung model control
This section includes the following controls for the lung model:

- *Toggle (ShowModel)*: Enables or disables the 3D view of the lungs.
- *Buttons (FixModel/ModifyModel)*: lock or unlock model manipulation.
  - In “locked” mode, the model remains fixed in space.
  - In “modifiable” mode, you can scale, rotate, and translate the model using natural gestures.
- An opacity slider adjusts the transparency of the lung model to provide a layered visualisation of the anatomical content (see Figure 4.5a and 4.5b).



(a) (b)

Figure 4.5: HoloLens 2 AR lung model control. (a) 3D lung model overlaid, manipulable via gestures. (b) Adjusted model opacity revealing an internal nodule (pink).

Lung nodules, integrated into the model as separate meshes with “Target” tags, remain visible at all times, even in the case of total opacity of the lungs, ensuring constant visualisation of the surgical target.

Mobile image plane control
This section allows the user to manage advanced interactions with the moving image plane, providing tools that are particularly useful for exploring deep lung regions and analyzing the spatial relationship between a nodule and the rib cage.

- *ImageOFF*: Disables/enables display of the moving image plane.
- *ClipLungOFF*: activates a “clipping” display mode, showing only the part of the model beyond the moving image plane and virtually cutting off the anterior structures.
- *FixImageOFF*: locks the moving image plane in its current position relative to the anatomical model.

Dedicated biopsy section

The Biopsy Tools subsection offers a comprehensive panel for planning the biopsy procedure. Three toggles allow individual activation of:

- A complete model of all structures/organs (affected side only) (Figure 4.6a).
- Thoracic cage and bone structures (Figure 4.6b).
- Airway and bronchial structures (Figure 4.6c).

A slider is associated with each model to adjust the opacity. The fourth toggle enables or disables the 3D model of the skin surface. The fifth toggle enables the display of a virtual biopsy needle positioned in the scene according to an optimal path calculated during analysis.

FixNeedle button: enables the needle to be blocked once the trajectory has been defined, preventing further accidental manipulation (Figure 4.6d).

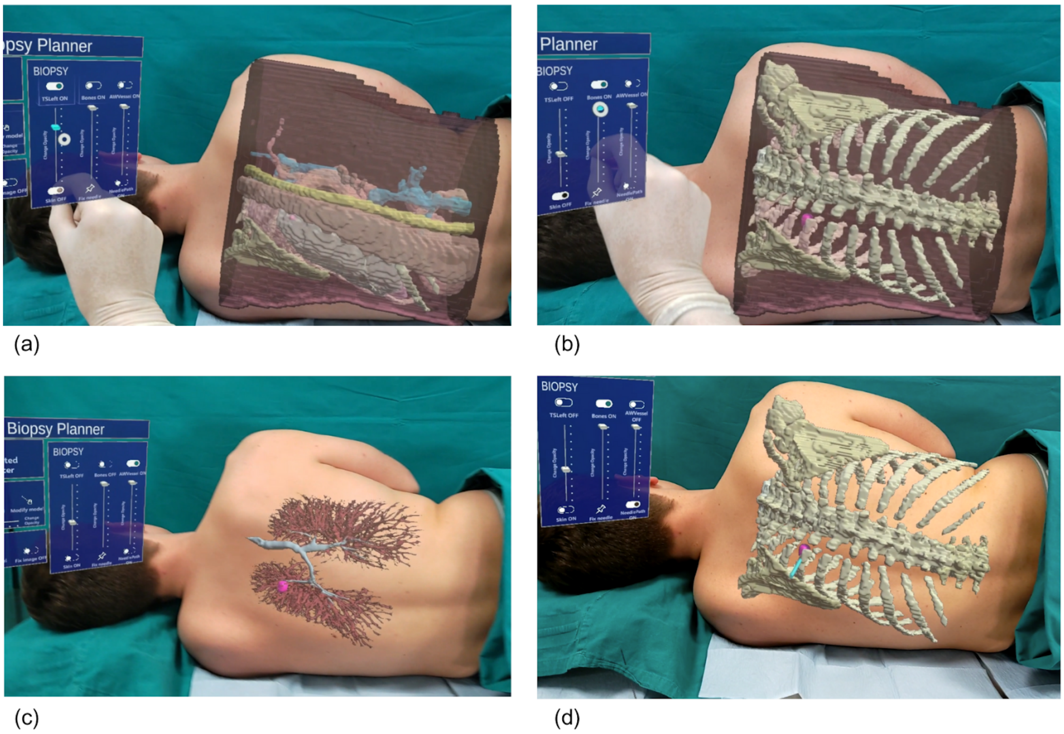


Figure 4.6: AR planning views via "Biopsy Tools" UI: (a) All structures. (b) Bones. (c) Airways & nodule. (d) Needle path, skin off.

C# supporting scripts

NeedleColorChange.cs This script provides real-time visual feedback on the needle during interaction with anatomical models using a trigger collider system, dynamically changing its color or material based on object tags to enhance accuracy and spatial awareness during biopsy procedure simulation.

- Tag “Bone”: red colour to indicate collision with rib (error/risk) (Figure 4.7a).
- Tag “Target”: green colour for the correct nodule reached (Figure 4.7b).

- No collision: neutral colour.

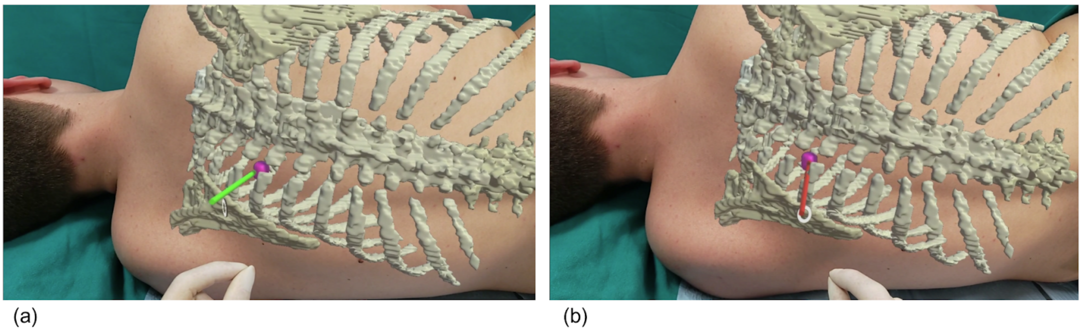


Figure 4.7: (a) Green needle (safe/target reached). (b) Red needle (bone collision).

PressableButtons.cs This is the main script responsible for managing interactions with buttons, models, and scene logic. Key functionalities include:

- Dynamic loading of segmented model prefabs and their positioning in the hierarchy.
- Visual state management (mobile/fixed) and colour/material updating.
- Opacity control via the MRTK slider.
- Activation/deactivation of manipulation components (ObjectManipulator).
- Integration with 3D Slicer for model synchronisation via OpenIGTLink.

SwitchButtons.cs This script manages the interaction and display of multiple anatomical 3D models within the mixed reality environment. The main functionalities include:

1. Lung clipping management
   - *OnClipLungON*: assigns a dedicated material that allows the model to be visually “clipped” for detailed analysis.
   - *OnClipLungOFF*: restores the original material, eliminating the clipping effect.
2. Controlling the visibility of anatomical models For each anatomical model (lung, bones, vessels, needle path, skin), pairs of *OnTurnModelON* and *OnTurnModelOFF* functions are implemented to control their activation and deactivation:
   - When activated (ON), the model is made visible, and the *SetMaterialToFade* function is applied to the material to enable transparency effects.
   - When deactivated (OFF), the model is hidden, and interface labels are updated.
3. Management of 2D images (image planes) The *OnShowImageON* and *OnShowImageOFF* functions control the visibility of moving and fixed image planes. During activation, a coroutine (*listeningRoutine*) is started that manages the real-time update of data from 3D Slicer.

4. Transparency Support Function

   The function *SetMaterialToFade(GameObjectTheModel)* runs through all the renderers of the model and sets the material to “Fade” mode, modifying the blending and depth-writing parameters to achieve transparency effects optimised for anatomical visualisation.

5. Technical considerations and optimisations

   The implementation process demanded meticulous attention to numerous technical aspects:

   - The performance of the HoloLens 2 device has been enhanced by mesh optimisation, which has been implemented to ensure the maintenance of a stable framerate.
   - The interface design should be intuitive, with the understanding that non-technical users will be the primary demographic.
   - In the context of information technology, security is defined as the process of input validation and error management with the objective of preventing unexpected behaviour.
   - The scalability of the system is facilitated by its modular architecture, which allows for the addition of new features.

6. Preliminary setup validation

   A technical evaluation of the system was conducted at the MITIC laboratory (Molinette, Turin) with the involvement of an internal volunteer, who had obtained prior authorisation, with the objective of assessing the efficacy of the loading of 3D models, the integration of the system with 3D Slicer via OpenIGTLink, and the AR interaction with HoloLens 2.

4.3 Application results of the biopsy planning module in 3D Slicer

Description of user interface components

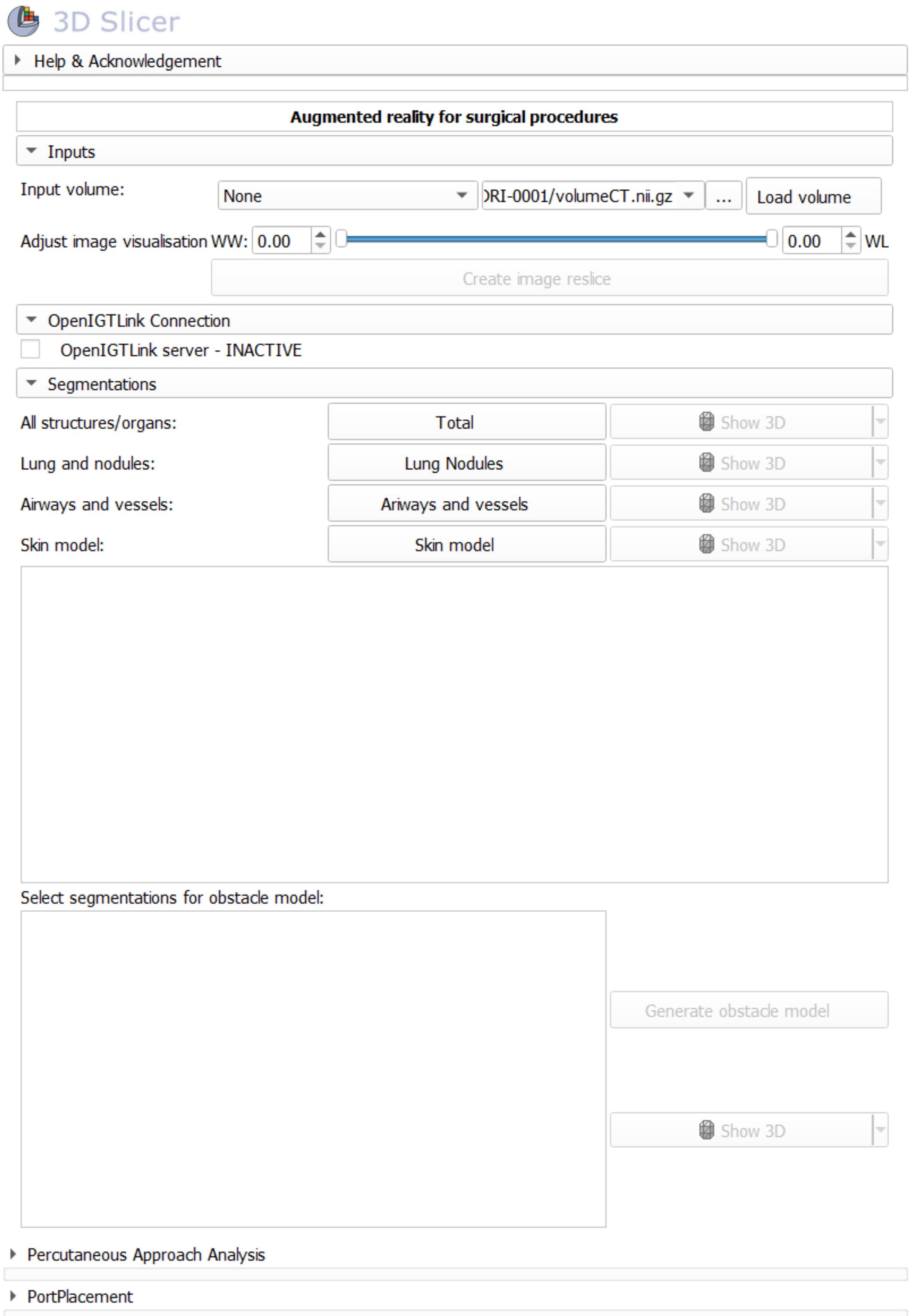


Figure 4.8: Overview of the LungNoduleBiopsyPlanner module's user interface

The LungNoduleBiopsyPlanner module's user interface, shown in Figure 4.8, combines an intuitive design with detailed control over the process steps; it is organized into sequential, collapsible sections that guide the operator through the planning workflow, from initial data selection to the definition and visualization of the biopsy path. The main sections and their controls are analysed below.

1. Input Section (Input Data Management)
   This section is dedicated to managing the volume of medical images forming the basis for planning.

   - Input volume: A drop-down menu allows the user to select the relevant volume of images from those already loaded into the MRML (Medical Reality Modelling Language) scene in 3D Slicer. This is typically a series of CT images of the thorax. Selecting this volume is a prerequisite for all subsequent operations.

   - Load volume: A button that opens the standard Slicer dialogue box for importing data when pressed. The user can then load a new dataset (e.g. DICOM, NIfTI, or NRRD format) directly from the file system. Once loaded, the volume becomes available in the 'Input volume' drop-down menu.

   - Adjust image visualisation (WW/WL): A slider for interactive adjustment of the windowing parameters, for example, the width (Window Width, WW) and level (Window Level, WL) of the CT image visualisation window. This feature is crucial for optimising the contrast and brightness of images in 2D views (axial, sagittal, and coronal), facilitating the identification of subtle anatomical structures, organ contours, and, above all, pulmonary nodules.

   - Create image reslice: A button responsible for the resampling process of the input volume. Reslicing can be utilised for the purpose of standardising the orientation and resolution of the volume, or alternatively, for generating orthogonal views aligned to specific structures.This optimises visualisation and processing for subsequent segmentation and integration with AR systems that require a specific coordinate system.

2. 'OpenIGTLink Connection' section

   This section handles real-time communication with external devices and applications. This communication is essential for integration with the AR system and follows the approach demonstrated by Pose-Díez-de-la-Lastra et al. [2].

   - OpenIGTLink server switch (Active/Inactive): This is a toggle switch that allows the OpenIGTLink server embedded in the module to be started or stopped. As discussed in Section 3.1.4, when OpenIGTLink is activated, the LungNoduleBiopsyPlanner module can transmit processed data (e.g., current CT slice images and spatial transformations) to a client application (e.g., the AR interface developed in Unity) in real time. This two-way communication is essential for displaying planned data superimposed on the patient's actual anatomy in real time during the AR-guided procedure.

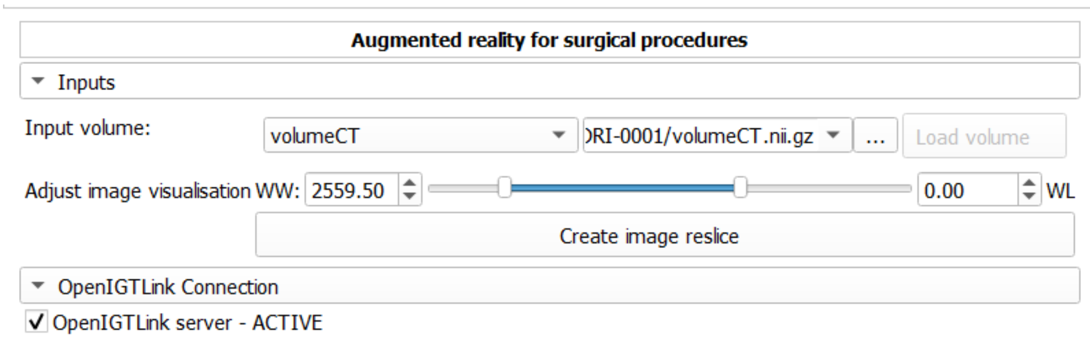


Figure 4.9: Input and OpenIGTLink Connection section of LungNoduleBiopsyPlanner UI

3. The segmentation section (segmentation of anatomical structures).

   Segmentation is the process through which the different anatomical structures in the CT volume are identified and isolated. This module uses the TotalSegmentator extension of 3D Slicer (see Section 3.2) for this step. This section enables the results of the segmentation to be displayed as 3D models.

   - Show 3D buttons for different anatomical structures:
     - Total: This activates the display of an all-inclusive 3D model which includes all the major anatomical structures identified by the TotalSegmentator extension (e.g., the lungs, heart, liver, kidneys, spine, rib cage, and large vessels). This provides a general anatomical context.
     - Lung nodules: Displays a 3D model of the lungs and any identified lung nodules. This is crucial for locating the biopsy target.
     - Airways and vessels: It shows the 3D model of the tracheobronchial tree and the main pulmonary vasculature. These models are important for planning routes that avoid damaging these structures.
     - Skin model: It generates and displays a 3D model of the external surface of the patient's chest, derived from body contour segmentation (see section 3.3.1). This model defines the entry point for the needle, and its generation follows a specific process.

     Each of these buttons allows the user to activate or deactivate the visibility of the respective model in Slicer's 3D view.

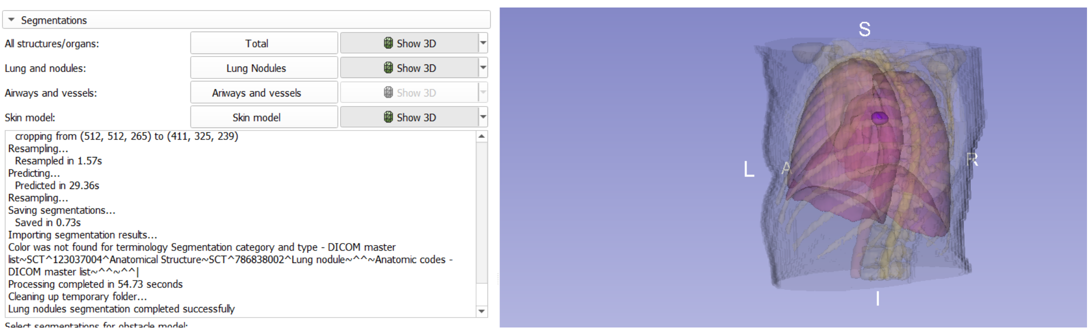


Figure 4.10: "Segmentations" section of LungNoduleBiopsyPlanner UI (left) and resulting 3D Slicer view (right) showing segmented lungs, nodule, skin, and ribs.

4. Obstacle model section This section is dedicated to the creation of a 3D model that specifically represents the anatomical structures that are critical obstacles during needle insertion.

   - Select segmentations: This is an interactive list that lists the different segmented structures (e.g. 'left rib 1', 'right rib 1', 'sternum', 'thoracic vertebrae'). The user can select the components that will form the obstacle model from this list.
   - Generate obstacle model: A button that, when pressed, combines all the selected bone segmentations into a single, unified 3D model, as described in Section 3.3.1. This 'obstacle model' (e.g., the rib cage) will later be used by the route planning algorithm to identify and discard trajectories that intersect these structures, thus ensuring the safety of the proposed route.

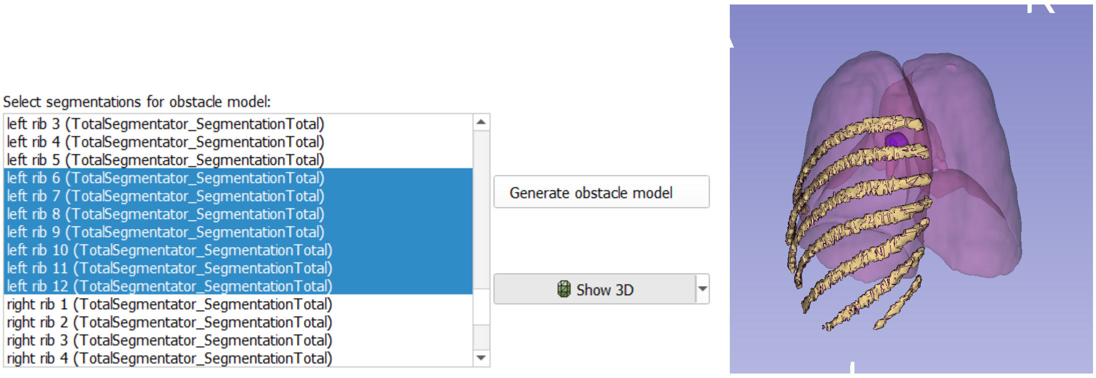


Figure 4.11: Obstacle model generation section of LungNoduleBiopsyPlanner UI (Left), Selecting rib segmentations. (Right) The resulting 3D rib cage model.

5. PAA section: This section of the LungNoduleBiopsyPlanner module acts as a centralised control panel for needle path planning. This planning leverages the capabilities of existing Slicer modules, including the PAA module and the Port Placement module. These modules' algorithmic and conceptual foundations were previously described in Section 3.3. This interface is designed to simplify interaction with these external modules within the LungNoduleBiopsyPlanner, guiding users through configuration of the necessary parameters, initiation of analysis and exploration of generated results from a single control panel. The subsection "Parameters'" allows the user to specify the essential input data that will be passed to the PAA module for analysis of the pathway:

   - Target point: A drop-down menu allows the selection of the fiducial point indicating the destination of the needle, which is an essential input for the PAA module.
   - Skin model and obstacle model: Two drop-down menus allow the respective 3D models to be assigned. These models are crucial geometric inputs for the analysis performed by the PAA module (see Section 3.3).
   - Opacity for skin model and obstacle model: Two sliders control the transparency of these models in the 3D view to improve visualisation of the context in which the PAA module operates.

- Start PAA analysis: This is a button that, when pressed, invokes the PAA module and passes it the parameters configured here to execute the path calculation algorithm (Section 3.3).

Once the PAA module has finished analysing the data, the “Outcome” section displays the results and provides tools for interactive exploration. This reflects the inherent visualisation and analysis capabilities of the PAA module.

- Colour mapped skin: A checkbox to activate or deactivate displaying the accessibility map on the skin model’s surface, generated by the PAA module.
- Accessibility score: A label showing the quantitative accessibility score value calculated and provided by the PAA module.
- All paths (Yellow): A checkbox to show or hide all valid paths calculated by the PAA module.
- Number of all paths: A label showing the total number of valid paths identified by the PAA module.
- Slider/Individual path selection box: This is a control that allows you to select and inspect the paths returned by the PAA module individually. These paths are dynamically highlighted in the 3D view.
- ’Create point on the path’: A button to add a new fiducial point along the selected path to facilitate the use of PAA results.
- ’Delete the created paths’: A button to remove paths calculated by the PAA module from the scene.

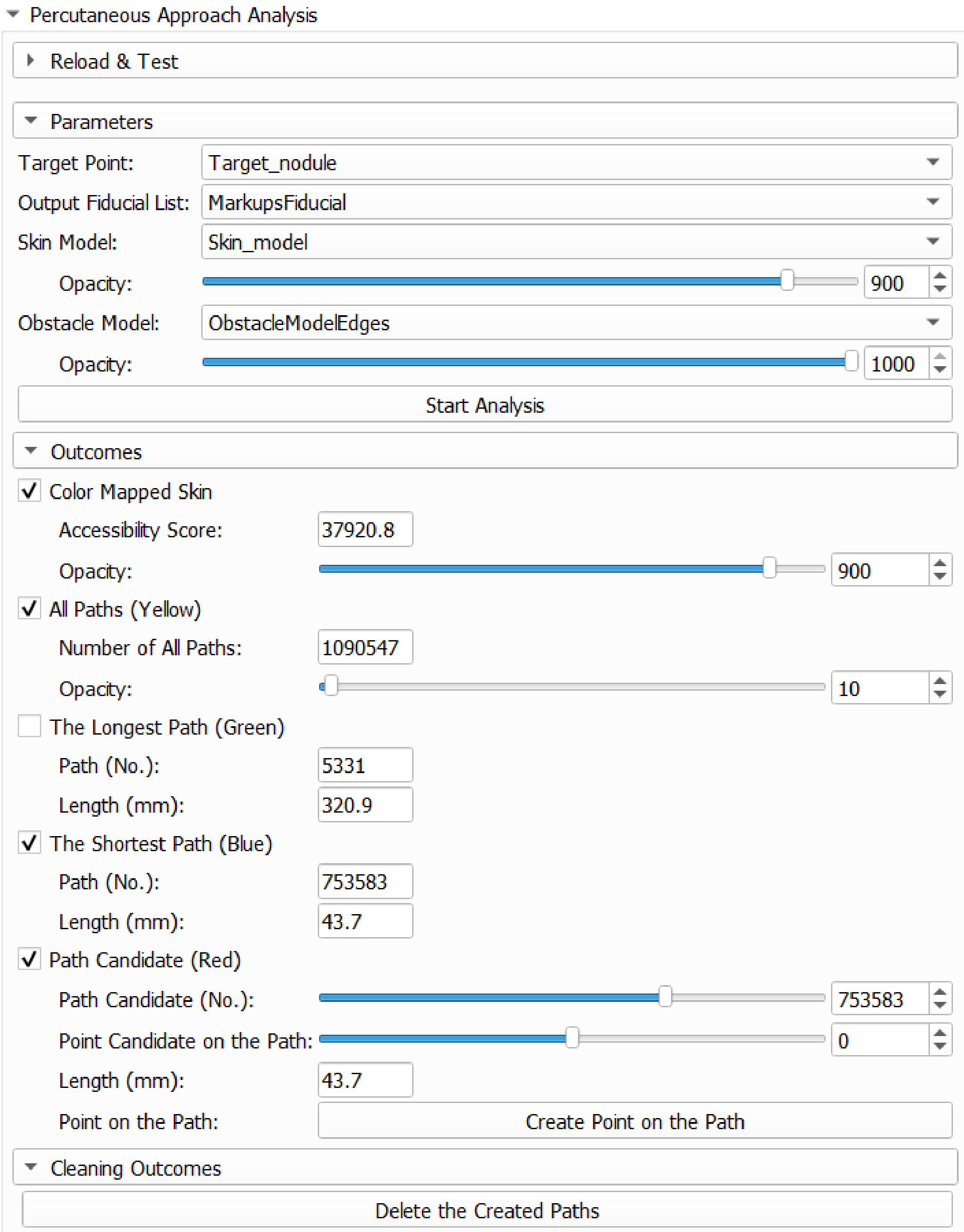


Figure 4.12: "PAA" section of LungNoduleBiopsyPlanner UI, showing input parameters and outcome visualization controls.

The area of PortPlacement in this interface is dedicated to configuring parameters for visualising the biopsy needle simulation, which will then be performed using the PortPlacement Slicer module's functionality (Section 3.3.2).The controls here prepare and pass the necessary data to this module.

- Surgical target: A drop-down menu for selecting the target point to be used by the PortPlacement module.
- Aim tools at target: This is a checkbox which, when activated, pre-configures the

orientation of the tool that will be displayed and managed by the PortPlacement module.

- Tool orientation: A set of sliders for fine-tuning the orientation parameters to be passed to the PortPlacement module.
- Tool radius and tool length: Input fields to define the geometric dimensions of the virtual tool. These parameters will be used by the PortPlacement module for simulation purposes.

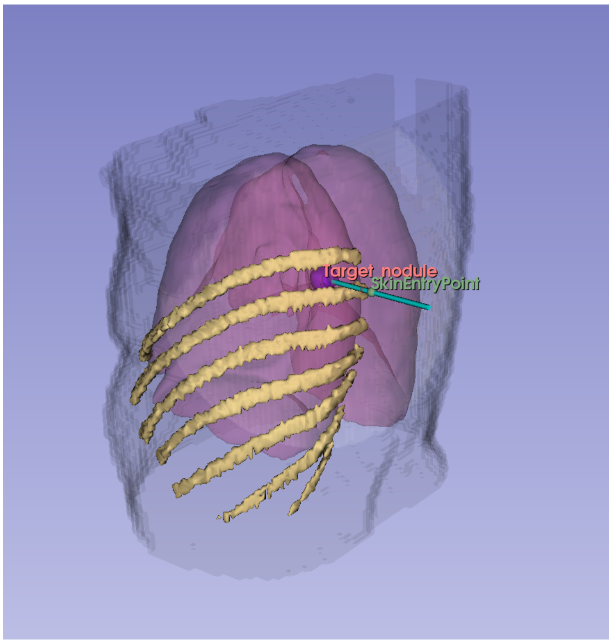


Figure 4.13: 3D Slicer view of virtual biopsy needle simulation using PortPlacement tools. Virtual needle (cyan) aimed at target nodule (purple) within 3D models of lungs (pink), ribs (yellow), and skin (gray).

6. Integration with 3D Slicer standard views

   The effectiveness of this extension also stems from its close integration with the standard views and functionalities of 3D Slicer. The user interacts not only with the module panel, but also with:

   - 2D views (Axial, Sagittal and Coronal): These views are essential for the detailed inspection of original CT images, the precise adjustment of window/level parameters, the accurate positioning of fiducial points (such as the target point on the nodule), and the visual verification of the alignment of calculated paths with anatomical structures.
   - 3D view: This configuration facilitates a 3D representation of the scene, thereby enabling concurrent visualisation of segmented anatomical models (skin, internal organs, obstructive masses, and nodules),calculated needle trajectories (including all valid trajectories and the selected one), and virtual instrument simulation. This perspective is invaluable for understanding complex spatial relationships and evaluating the suitability of the biopsy plane.

4.4 Usability testing with surgeons

A preliminary usability test was conducted to evaluate the usability, comprehensibility and potential clinical relevance of the developed AR system, LungNoduleBiopsyPlanner. This evaluation aimed to gather quantitative and qualitative feedback on the user experience from a diverse group of physicians, in order to identify the system's strengths and areas requiring improvement.

4.4.1 Test methodology

The test involved three professionals with different profiles and levels of experience: a robotic engineer with 0–5 years' experience in robotic surgery, a general surgeon with 6–10 years' experience, and a radiodiagnostics specialist with 0–5 years' experience. This mixed composition, which included both end users (surgeons and radiologists) and a user with a strong technical background, was chosen to ensure a comprehensive evaluation from complementary perspectives. Participants' previous experience with AR/MR technologies and 3D planning software ranged from 'little' to 'moderate', ensuring an evaluation from different perspectives.

Each participant's testing session began with a brief introduction to the Microsoft HoloLens 2 device and the AR system. Each user was then asked to wear the headset and perform the eye calibration procedure, which is essential for correctly displaying holograms. The surgeons were then given the opportunity to freely explore the various features of the LungNoduleBiopsyPlanner system. They interacted with the 3D anatomical models, tested the manipulation of holograms, viewed the CT slices synchronised by 3D Slicer and simulated the positioning of the biopsy needle. At the end of the practical session, each participant was given two questionnaires: a customised one to evaluate specific aspects of the application, and the System Usability Scale (SUS) to provide a standardised measure of overall usability.

4.4.2 Quantitative results: Questionnaire analysis

Analysis of the collected quantitative data provides an initial, encouraging assessment of the system.

Specific evaluation of the AR application

The results of the customized questionnaire, which used a 5-point Likert scale (where 1 = "Strongly disagree" and 5 = "Strongly agree"), are summarized in Table 4.1. The system was perceived positively overall.

Regarding the user interface and visualisation, participants found menu navigation relatively easy and intuitive, with an average score of 4.33/5, and manipulation of 3D models relatively easy, with an average score of 3.67/5. The visual quality and level of detail of the holographic models were positively rated (average: 4/5), and the immersive 3D visualisation was considered to be very useful for understanding spatial relationships (average: 4.67/5). Responsiveness to gesture commands received a more mixed evaluation (average: 2.67/5), indicating an area for potential improvement.

In terms of clinical utility, the system scored highly. Participants recognised the usefulness of synchronised CT slices (average score: 4.67/5) and agreed that the AR system improved their ability to understand the optimal needle path (average score: 4/5).

The needle placement simulation was also considered useful (average score: 4/5), and the visual feedback was considered informative. Overall, participants considered the system to be a useful tool for preoperative planning (average rating: 3.67/5). There was strong consensus on the system's potential for intraoperative use (average score: 4.67/5).

Regarding the HoloLens 2 experience, the headset's comfort was rated as good (average: 2.67/5) and perceived visual fatigue was minimal (average: 4.33/5 on a direct scale).

System Usability Scale (SUS)

The System Usability Scale (SUS) is a tool designed to evaluate the ease with which a system can be used by a user.

The System Usability Scale (SUS) results, detailed in Table 4.2, revealed scores of 72.5, 75.0, and 57.5 across the three participants. The mean SUS score for the system is 68.33. According to standardised benchmarks for interpreting the SUS [30], a score of 68 is considered the average threshold. The result falls precisely within this average range, indicating "OK" or "acceptable" usability, with room for enhancement but an absence of significant perceived usability issues. The responses indicate that the system was perceived as not overly complex (average: 2/5) and its functions were considered to be reasonably integrated (average: 4/5). However, interaction was judged to be cumbersome at times (average: 2.67/5), in line with comments on gesture responsiveness.

4.4.3 Qualitative results: themes emerging from feedback

The analysis of open-ended responses provided insights that were found to be of great significance, thus enriching the quantitative data.

- Recognised Strengths: All participants identified immersive 3D visualisation as the primary strength. The 'tissue layering and reconstruction', 'detailed visualisation of the vascular system' and 'real-time DICOM visualisation' synchronised by Slicer were particularly well received. The capacity to comprehend anatomical relationships and evaluate obstacles (costal, vascular) in three dimensions was regarded as a substantial benefit for advancing with greater assurance and expediency in the planning process.

- Limitations and suggestions The primary criticisms centred on interaction and performance. The manipulation of holograms using gestures for alignment with the patient was found to be 'cumbersome', and was deemed 'too imprecise' for direct intraoperative use. It was determined that enhancement of image stability and responsiveness to gesture commands would be advantageous. One participant correctly noted the challenges associated with dependence on a remote workstation for streaming and potential latency in shielded environments, such as a CT room. A key recommendation that emerged from this study was the implementation of a manual needle trajectory correction mode, which would serve to complement the existing automatic guidance system and offer the operator a greater degree of control.

- Clinical potential and future impact: There was a strong consensus on the clinical potential of the system, especially with regard to preoperative planning of complex biopsies (for 'hard-to-reach nodules') and for the training of residents. There was unanimous consensus among participants that the utilisation of the system prior to surgery could exert a favourable influence on the intraoperative phase, enabling them to 'progress more expeditiously, select the optimal trajectory from the outset, and proceed with greater confidence by avoiding multiple intermediate scans, resulting in reductions in both time and dose.' In regard to future intraoperative utilisation, participants placed significant emphasis on the necessity for a model-patient alignment system that is both more robust and less cumbersome than manual gestures.

	Question	Mean
Q1	Navigating and finding the desired features in the menu was easy.	4.33
Q2	Manipulating (rotating, scaling, positioning) holographic 3D models was intuitive.	3.67
Q3	The system was responsive to gesture commands.	2.67
Q4	The visual quality and level of detail of the holographic 3D models (lungs, nodules, etc.) were high.	4.00
Q5	The immersive 3D visualisation was useful for understanding the spatial relationships between the target nodule and surrounding anatomical structures.	4.67
Q6	The CT slices synchronised by 3D Slicer (fixed and moving image planes) were useful for exploring the volume.	4.67
Q7	Exploring the volume using CT slices synchronised by 3D Slicer was unclear.	1.67
Q8	The AR system improved my ability to visualise and understand the optimal biopsy needle path.	4.00
Q9	The AR system did not offer a significant improvement in understanding the optimal needle path compared to traditional methods.	1.67
Q10	Needle placement simulation and visual feedback (e.g., colour change) were useful for assessing the trajectory.	4.00
Q11	Visual feedback during needle placement simulation (e.g., colour change) was uninformative.	2.33
Q12	Overall, I believe this AR system is a useful tool for preoperative planning of lung biopsy.	3.67
Q13	Overall, the usefulness of this AR system for preoperative planning of lung biopsy is limited.	2.00
Q14	I believe that the visualisation features of this system could also be useful during the intraoperative phase (e.g. to guide needle placement).	4.67
Q15	I do not see a clear use for this system during the intraoperative phase.	1.33
Q16	Wearing the HoloLens 2 headset during the session was comfortable.	2.67
Q17	The HoloLens 2 headset was uncomfortable to wear for the duration of the session.	2.67
Q18	At the end of the session, I experienced minimal visual fatigue.	4.33
Q19	At the end of the session, I experienced significant visual fatigue.	1.67

Table 4.1: Results from the custom AR application questionnaire. Mean scores from the three participants (robotic engineer, general surgeon, and radiology resident) on a 5-point Likert scale (1 = Strongly disagree, 5 = Strongly agree) for specific questions regarding the LungNoduleBiopsyPlanner's user interface, visualization quality, clinical utility, and HoloLens 2 ergonomics.

	Question	Mean
Q1	I think that I would like to use this system frequently.	4.00
Q2	I found the system unnecessarily complex.	2.00
Q3	I found the system easy to use.	3.33
Q4	I think that I would need the support of a technical person to be able to use this system.	3.00
Q5	I found the various functions in this system were well integrated.	4.00
Q6	I thought there was too much inconsistency in this system.	1.67
Q7	I imagine that most people would learn to use this system very quickly.	3.67
Q8	I found the system very cumbersome to use.	2.67
Q9	I felt very confident using the system.	3.33
Q10	I needed to learn a lot of things before I could get going with this system.	1.67

Table 4.2: System Usability Scale (SUS) questionnaire results [30]. Mean scores from the three participants on the 10 standard SUS statements, rated on a 5-point Likert scale (1 = Strongly disagree, 5 = Strongly agree). This table provides the data used to calculate the overall mean SUS score of 68.33 for the LungNoduleBiopsyPlanner system.

Chapter 5

Discussion

The integration of AR in preoperative surgical planning, as demonstrated by the LungNoduleBiopsyPlanner system, has the potential to offer a range of practical and potential benefits that might enhance preparation standards and, consequently, the outcomes of procedures, particularly in complex scenarios such as lung biopsies. Analysis of the system's functionality and preliminary user feedback suggests that integrating AR could provide valuable support for surgical planning by introducing innovative elements that complement existing practices.

5.1 Benefits of AR for surgical planning

The primary and most intuitive benefit of AR is its ability to transform complex medical data into immersive, contextualised 3D visualisations. Unlike interpreting 2D CT slice sequences, which requires considerable cognitive effort to reconstruct the anatomical volume mentally, AR systems such as the LungNoduleBiopsyPlanner allow interactive 3D holographic models of the lungs, target nodules, the bronchial tree and intricate vascular structures to be displayed directly in the user's physical space or, prospectively, superimposed on the patient themselves. These holograms can be manipulated and viewed from any angle, potentially providing a deeper and more intuitive understanding of the spatial relationships between the target lesion and the delicate adjacent anatomical structures. Surgeons could thus 'navigate' virtually within the patient's anatomy, acquiring a spatial awareness that 2D visualisation can hardly match — an important consideration, especially in the presence of anatomical variants or complex pathological conditions [5].

An enhanced spatial understanding leads directly to more accurate, efficient, and, above all, safer planning of the biopsy path. Our system integrates AR visualisation with the path calculation capabilities of modules such as PAA [18], enabling surgeons to evaluate multiple access trajectories to the nodule in a 3D environment. Simultaneously visualising the target nodule, anatomical obstacles (such as ribs and large vessels, which are segmented and modelled), and vital structures to be avoided enables the selection of a path that optimises target achievement while minimising risks. Dynamic visualisation of CT slices is synchronised in real time by 3D Slicer and projected through the holographic 3D model thanks to integration with OpenIGTLink. This could offer an excellent level of control and verification. The surgeon can virtually 'slice' the model along the proposed needle trajectory and examine its relationship with internal structures at each level. Interactive visual feedback, such as the virtual needle changing colour to signal potential collisions with bone structures, acts as an additional safety mechanism, guiding the user towards defining an optimal biopsy plan.

Current percutaneous biopsy procedures often require the repeated use of intraoperative imaging (e.g., CT guidance or fluoroscopy) to confirm the position of the needle and its advancement towards the target. This results in exposure to ionising radiation for both the patient and the medical team, as well as potentially extending the procedure time. Preliminary feedback gathered from surgeons who tested the LungNoduleBiopsyPlanner (as discussed in Section 4.4) suggests that preoperative planning enriched by AR could make such intraoperative checks unnecessary. If surgeons can approach procedures with an extremely detailed, 3D mental map of the target area, derived from AR exploration, their confidence and precision in guiding the needle could increase to such an extent that fewer verification scans would be required, with obvious benefits in terms of radiological safety and procedural efficiency.

Thanks to its immersive and easily shareable nature, AR visualisation could serve as a unifying platform for discussing clinical cases. In the context of LungNoduleBiopsyPlanner specifically, interacting with patient-specific data processed in 3D Slicer via an intuitive AR interface on HoloLens 2 could facilitate communication and strategic alignment between interventional radiologists, thoracic surgeons, oncologists, and other specialists involved in the care pathway.

Beyond their direct application in planning specific cases, AR systems such as the one presented here are valuable educational tools. The literature widely supports the use of AR to revolutionize medical training [31]. They allow surgeons in training, residents, and even experienced surgeons approaching new techniques to explore the 3D anatomy of real clinical cases in an immersive, interactive environment. This enables them to simulate the planning of complex approaches and understand the specific anatomical challenges of each patient. This offers a learning experience that is difficult to replicate with traditional methods. This virtual 'hands-on' approach can accelerate learning, improve retention of anatomical knowledge, and prepare surgeons to perform real-life procedures with greater competence and confidence. An important aspect is the way users interact with the system. The use of gesture and voice commands, made possible by HoloLens 2 and optimised through the MRTK, offers a more natural and fluid alternative to the traditional mouse-and-keyboard setup. This is particularly advantageous in contexts that simulate or precede the sterile environment of the operating theatre, where 'contactless' manipulation of data and 3D models can reduce cognitive load and improve the efficiency of the planning workflow.

The principle of personalised treatment is at the core of modern medicine.The ability to generate high-fidelity 3D anatomical models directly from individual patients' CT images and use these models as the basis for detailed surgical planning is a fundamental step in this development. AR amplifies this personalisation, offering surgeons the opportunity for true 'virtual immersion' in their patients' unique anatomy, enabling planning that is both patient-specific and tailored to their preferences and skills.

5.2 Challenges encountered and proposed solutions

The exciting and undeniable potential of AR to transform surgical planning, as demonstrated by the development of the LungNoduleBiopsyPlanner system, is accompanied by a series of intrinsic technical and ergonomic-cognitive challenges. During the design, implementation, and initial testing phases, we encountered some of these obstacles while seeking possible solutions, with the ultimate goal of making AR technology an increasingly effective and integrated tool in everyday clinical practice.

One of the fundamental issues, and perhaps the most pressing, concerns the accuracy with which 3D holographic models overlap with actual anatomy. Even minimal discrepancies in alignment, caused by almost imperceptible patient or HoloLens 2 headset movements, or subtle initial calibration inaccuracies, can affect the visual guidance's reliability. To mitigate this issue, we recognised the importance of robust registration algorithms and the use of multiple anatomical landmarks. Although integrating external tracking systems increases the complexity of the setup, we believe it is necessary to ensure accurate and stable alignment. Relying exclusively on manual micro-adjustments by the surgeon can be ineffective and unreliable during surgery.

At the same time, careful consideration has been given to the quality of holographic visualisation and system performance. Although the field of view of the HoloLens 2 has improved compared to the previous generation, it remains more limited than natural vision. The fluidity and stability of holograms can also be affected by the complexity of the loaded 3D models. We have therefore worked to optimise the meshes exported from 3D Slicer, for example, using decimation techniques, and have explored the use of efficient shaders in Unity to better manage transparency and occlusion. These are important factors to avoid overloading the surgeon's visual perception.

Interacting with the system is another important aspect. Although the hand gestures and voice commands offered by HoloLens 2 and managed via MRTK aim for natural interaction, they inevitably require a learning period. Not all users are immediately comfortable with them, and accuracy can vary. Designing a floating, intuitive, and non-invasive user interface was therefore an iterative process guided by feedback and aimed at optimising the user experience.

Finally, the technical integration of the various software components- 3D Slicer, Unity, and HoloLens 2 - via the OpenIGTLink protocol required careful engineering to ensure low-latency communication and correct data synchronisation. This included the complex management of different coordinate systems. The modularity of the Slicer architecture and the flexibility of Unity were key to addressing these challenges. Lastly, the cost of hardware and custom software development remains a pragmatic consideration for wider deployment; however, the use of open-source platforms, such as 3D Slicer and toolkits, such as MRTK, helps offset some of these costs.

Overcoming these challenges requires an ongoing commitment to research and development, close collaboration between engineers and clinicians, and a meticulous evaluation of the impact of these technologies on clinical outcomes and the efficiency of the healthcare system.

5.3 Clinical impact and future perspectives

Beyond its inherent technical complexities, the LungNoduleBiopsyPlanner system and its AR approach could demonstrate significant clinical potential. This might have a positive influence on thoracic surgery and pave the way for further innovations. The implications range from immediate improvements in the preoperative phase to future intraoperative applications.

The most direct clinical impact, as confirmed by preliminary feedback from clinicians (see Section 4.4), is an improvement in preoperative planning. The system's ability to present patient-specific 3D models to surgeons in an immersive, interactive environment transforms anatomical analysis. The surgeon can manipulate the hologram of the lungs directly, rotating it to examine it from every angle and using virtual tools such as the dynamic cutting plane synchronised with the CT slices from 3D Slicer to virtually dissect the model along a hypothetical needle trajectory. This interaction could allow for a more accurate assessment of the optimal angle and depth of insertion by simulating the operating room perspective. This level of detail and interactivity might improve the understanding of complex spatial relationships between the nodule and surrounding vital structures, potentially enabling more precise and informed biopsy planning. As a result, this could lead to increased confidence in the surgical approach and possibly contribute to a reduction in the risk of complications.

Improved accuracy in planning has a direct impact on the need for intraoperative imaging. If the nodule access strategy has been defined in great detail and with high confidence in the preoperative phase thanks to AR, the need for repeated radiological checks during surgery may decrease. Clear internalisation of the optimal trajectory, supported by immersive visualisation, can guide the surgeon more confidently, leading to reduced procedure times, costs, and radiation exposure for patients and staff.

In considering future developments, it is evident that the most logical progression for systems such as the LungNoduleBiopsyPlanner would be to expand their functionality to include intraoperative use, thereby transforming them from planning tools into real-time navigation systems.This would necessitate substantial further developments, such as the integration of patient and instrument tracking systems, and the implementation of dynamic registration algorithms capable of compensating for physiological movements and tissue deformations.

Another promising frontier is deeper integration with (AI). In addition to its current role in automatic segmentation with tools such as TotalSegmentator [14], AI could actively assist with planning in the future by suggesting optimised biopsy paths and analysing procedural risks on a patient-specific basis. It could also further automate the registration process between the virtual and real worlds. Finally, large-scale clinical studies will be crucial in fully validating the clinical value of these technologies and guiding their adoption. These studies must rigorously measure the system's impact on objective metrics such as sampling accuracy, operator time, radiation doses, and patient outcomes. Multidisciplinary collaboration and the definition of shared standards will be essential in refining these tools and integrating them effectively into surgical practice. Our LungNoduleBiopsyPlanner project aims to contribute to this effort by making thoracic surgery increasingly precise, safe, and personalised. Further details on these future developments will be discussed in Section 6.

Chapter 6

Conclusions and Future Work

The present thesis explored the application of technological evolution to medicine, specifically investigating and implementing an AR system to optimise preoperative planning for lung biopsies. Building on the challenges of locating small lung nodules and navigating complex anatomies discussed in the background, the project aimed to exploit the synergy between the 3D Slicer image processing platform and the Microsoft HoloLens 2 headset's immersive visualisation capabilities.

6.1 Results and contributions of the thesis

At the end of the research and development process, the key conclusions can be summarised as follows:

The primary contribution of this thesis is to demonstrate the technical feasibility of functional, real-time integration between 3D Slicer and Unity/HoloLens 2, mediated by the OpenIGTLink protocol. Inspired by Pose-Díez-de-la-Lastra et al. [2] and adapted for our use case, this architecture has enabled the creation of a prototype: the LungNoduleBiopsyPlanner. This prototype supports a more interactive planning workflow.

Using patient-specific 3D anatomical models generated through automatic segmentation with TotalSegmentator [14] and visualised as interactive holograms confirmed the potential of AR to enhance surgeons' 3D understanding of thoracic anatomy, as supported by previous research [5]. Preliminary feedback (Section 4.4) suggests that this improved perception could lead to more intuitive and informed biopsy planning.

Developing the system has also enabled us to identify and analyse technological and usability challenges that still exist, which are discussed extensively in Section 5.2. These include registration accuracy, limitations of HMD hardware, and the learning curve. This work therefore provides a realistic basis for understanding the obstacles to be overcome for full clinical adoption. Finally, the LungNoduleBiopsyPlanner module represents a step towards a more integrated and optimised planning workflow for lung biopsies by centralising several stages of the process.

6.2 Future prospects and directions for development

The conclusions drawn and challenges identified pave the way for numerous exciting developments in future work, to evolve the system from a promising prototype into a clinically validated and integrated tool.

The most ambitious objective is the transition to real-time intraoperative navigation. As mentioned in the discussion, this will require integrating accurate patient and instrument tracking systems, as well as developing dynamic registration algorithms that can compensate for physiological movements and tissue deformations. The scalability of the OpenIGTLink infrastructure provides a solid technical basis for this evolution and could significantly reduce dependence on conventional intraoperative imaging.

The role of AI is set to become increasingly significant. In addition to its current use in segmentation, it is expected to be used for automatically suggesting optimised biopsy trajectories, predicting procedural risks, and further automating registration processes. This will make the system more intelligent and proactive.

Rigorous, large-scale clinical validation studies will be crucial. These will need to go beyond usability testing in order to measure the actual impact of the AR system on objective metrics such as diagnostic accuracy, procedural times, radiation doses and clinical outcomes for patients. This will involve comparing theAR approach with current standards of care. Only through such studies will it be possible to quantify the real added value.

At the same time, the continuous optimisation of the user experience and ergonomics will remain a priority. Feedback from clinicians will inform the refinement of interfaces and modes of interaction. Technological advances in HMD devices promise improvements in terms of field of view, resolution and comfort. This will make AR easier and less invasive for the operator to use.

This thesis project has ultimately helped to shed light on the transformative potential of AR in lung biopsy planning. The LungNoduleBiopsyPlanner system is a concrete example of how the convergence of advanced imaging, AI, and immersive visualisation can pave the way for more precise, safer, and more personalised thoracic surgery, with the ultimate goal of improving patient care.

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