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eXtended Reality Support for Invasive Medical Procedures with Enhanced 3D Imaging

A dissertation submitted in partial satisfaction of the
requirements for the degree Doctor of Philosophy

in

Computer Science

by

Menghe Zhang

Committee in charge:

Professor Nadir Weibel, Chair
Professor Jürgen P. Schulze, Co-Chair
Professor Larry L. Smarr
Professor Edward J. Wang

2023

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The Dissertation of Menghe Zhang is approved, and it is acceptable in quality and form for publication on microfilm and electronically.

University of California San Diego

2023

DEDICATION

To my family and advisors for their dedication and unconditional support.

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In the late summer of 2016, I posted my first update to my friends and family about life at UCSD: a photo with a charismatic instructor on stage. That class happened to be CSE 167 computer graphics, taught by Professor Jurgen Schulze. I am immensely grateful to Jurgen for granting me the opportunity to engage in research. From the time of my Master’s studies, Jurgen has not only been a source of inspiration due to his exceptional professionalism and unwavering integrity but also because of his remarkable kindness and compassion towards others. Even if my path hadn’t led me toward a research-oriented direction, Jurgen would still serve as an exemplar for me to aspire to become a remarkable engineer.

In early 2021, I joined Nadir’s The Human-centered eXtended Intelligence Research Lab. This period was undoubtedly challenging for both the world and myself. The world was still grappling with the repercussions of a severe pandemic, causing many academic activities to unravel. Personally, I found myself in a transitional phase, with my previous project completed and uncertain about my next steps. Having had no prior knowledge about research in the human-computer interaction (HCI) field, I only possessed a fledgling interest in a particular direction: acupuncture. Nadir, however, assured me that he would offer his utmost support and encouraged me to establish connections independently on behalf of him and the lab. It’s possible that he had limited familiarity with this specific field at the time, yet he still encouraged me to explore it in the right manner. I was deeply impressed by his professionalism and his openness as a researcher, always embracing new concepts. As graduation approached, Nadir provided a comment in my evaluation form that left a profound impact on my research career. He stated, “In the last 2 years, she was extremely successful in learning and applying human-centered design and evaluation methodologies. She has developed key collaboration and worked hard on her research work in

these challenging settings.” This comment serves as a significant milestone for me, reinforcing my determination to fearlessly embark on new ventures, even if success is not guaranteed.

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As an atheist, I am constantly amazed by how the universe seems to guide me toward the place I deeply desire to be. All I have to do is follow my instincts and do the next right thing. I am acutely aware of how fortunate I have been thus far. Everyone I have met and everyone who has ever provided me with guidance has supported my inner drive to pursue seemingly impossible goals. Their profound knowledge and research skills have kept me on the right track.

This dissertation is divided into 8 chapters. Chapter 1 outlines the introduction and related works. Chapters 2 through 7 cover the solutions I developed to address the unique challenges of technical and user-centered designs. Chapter 8 summarizes the contributions of my work.

Chapter 2, is largely a reprint of the material as it appears in Zhang, Menghe, Karen Lucknavalai, Weichen Liu, and Jürgen P. Schulze. “Calar: A c++ engine for augmented reality applications on android mobile devices.” *Electronic Imaging* 32 (2020): 1-7. The dissertation author was the primary investigator and author of this paper.

Chapter 3, is largely a reprint of the material as it appears in Zhang, Menghe and Jürgen P. Schulze. “Server-Aided 3D DICOM Image Stack Viewer for Android Devices.” *Electronic Imaging, The Engineering Reality of Virtual Reality* (2021). The dissertation author was the primary investigator and author of this paper.

Chapter 4, is largely a reprint of the material as it appears in Zhang, Menghe, Weichen Liu, Nadir Weibel, and Jürgen P. Schulze. “A DirectX-Based DICOM Viewer for Multi-user Surgical Planning in Augmented Reality.” In *Advances in Visual Computing: 17th International Symposium, ISVC 2022, San Diego, CA, USA, October 3–5, 2022, Proceedings, Part II*, pp. 217-228. Cham: Springer Nature Switzerland, 2022. The dissertation author was the primary

investigator and author of this paper.

Chapter 5, is largely a reprint of the material as it appears in Zhang, Menghe, Jürgen P. Schulze, and Dong Zhang. “E-faceatlasAR: extend atlas of facial acupuncture points with auricular maps in augmented reality for self-acupressure.” *Virtual Reality* 26, no. 4 (2022): 1763-1776. The dissertation author was the primary investigator and author of this paper.

Chapter 6, in full, has been submitted for publication of the material as it may appear in *International Journal of Human–Computer Interaction*, 2023, Menghe Zhang, Chen Chen, and Nadir Weibel. The dissertation author was the primary investigator and author of this paper.

Chapter 7, in full, is currently being prepared for submission for publication of the material. Menghe Zhang, Chen Chen, Matin Yarmand, and Nadir Weibel. The dissertation author was the primary investigator and author of this paper.

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Zhang, Menghe, Junsong Zhang, and Dong Zhang. "ATVR: an attention training system using multitasking and neurofeedback on virtual reality platform." In 2019 IEEE International Conference on Artificial Intelligence and Virtual Reality (AIVR), pp. 159-1593. IEEE, 2019.

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Zhang, Menghe, Chen Chen, Matin Yarmand, and Nadir Weibel. "AcuVR: a Personalized Medical Imaging-Based Virtual Reality Acupuncture Training System." Currently being prepared for submission.

ABSTRACT OF THE DISSERTATION

eXtended Reality Support for Invasive Medical Procedures with Enhanced 3D Imaging

by

Menghe Zhang

Doctor of Philosophy in Computer Science

University of California San Diego, 2023

Professor Nadir Weibel, Chair
Professor Jürgen P. Schulze, Co-Chair

Invasive medical procedures are essential in healthcare, but clinicians can only be effective in performing them when they are able to precisely understand an individual patient's anatomy. While training and multi-year experience form the basis for any medical procedure, individualized medical imaging plays a critical and continuous role across both the educational context and the everyday practice of these procedures. As a result, with the improvement of technology and computer science, advanced visualization of medical imaging has emerged as a vital area of research. More recently, the widespread adoption of affordable XR (eXtended Reality) technology has opened the way to new exciting opportunities that aim to improve clinicians'

comprehension of spatial relations among anatomical structures and could revolutionize medical imaging visualization in various educational settings. While XR is promising to take medical imaging visualization to new heights, current XR systems do not cater to the specific requirements of diverse medical procedures, and important research work needs to address how to shape their customization and adaptation in those settings.

This dissertation introduces the design and implementation of systems and techniques that support the planning and treatment using various invasive medical procedures across the XR spectrum. It investigates clinical settings that span from invasive surgical procedures to contemporary acupuncture, derived from a traditional invasive procedure. Both of these clinical practices emphasize accuracy, safety, and evidence-based practice, but present different challenges when integrating technological advancements for enhanced comprehensive anatomy understanding, personal data interpretation, and visual guidance. We first show how to support surgical planning focusing on the utilization of smartphones, head-worn VR headsets, and optical see-through glasses, and then utilize a user-centered design approach to explore the requirements and design considerations for leveraging XR technology to empower training and treatment in acupuncture practice, including exploring how a novel VR acupuncture training system has the potential to be integrated into clinical practice in the near future. This research also sheds light on the potential synergies and relationships between traditional treatment and other minimally invasive procedures.

Overall, this dissertation's research contributes to the design and development of specialized XR systems tailored to the unique needs of different medical treatment scenarios. By extending the horizons of how various types of treatments can benefit from XR, this work broadens the potential applications and advantages of this technology.

Chapter 1

Introduction and Related Work

1.1 Introduction

Invasive medical procedures, ranging from intricate surgeries to contemporary acupuncture practices, are critical components of modern healthcare, demanding accurate, safety, and evidence-based practice. These procedures play a vital role in diagnosing and treating various medical conditions, offering patients improved quality of life and potential life-saving interventions. However, clinicians can only be effective in performing them when they are able to precisely understand an individual patient's anatomy. While training and multi-year experience form the basis for any medical procedure, individualized medical imaging plays a critical and continuous role across both the educational context and the everyday practice of these procedures. As a result, with the improvement of technology and computer science, advanced visualization of medical imaging has emerged as a vital area of research.

With the continuous advancement of technology, the integration of eXtended Reality (XR) technologies has emerged as a transformative approach to enhance the planning, training, and execution of these procedures. XR, encompassing virtual reality (VR), augmented reality (AR), and mixed reality (MR), offers immersive and interactive experiences that enable clinicians to visualize and manipulate digital models of patient-specific anatomy in three dimensions. By merging virtual and real-world environments, XR provides a unique method for clinicians to augment their perception, gain comprehensive insights into anatomy, interpret personalized data,

and receive real-time visual guidance.

While XR is promising to take medical imaging visualization to new heights, the successful integration of XR technologies into invasive medical procedures requires careful consideration of several factors. On the one hand, technical challenges such as data integration, device compatibility, real-time image processing, and 3D data rendering. On the other hand, user-centered design approaches play a crucial role in shaping the development of XR systems that cater to the specific requirements of diverse medical procedures and clinicians, emphasizing the importance of usability, and the impact on the outcomes.

This dissertation aims to delve into the design and implementation of XR systems and techniques that support various invasive medical procedures across the XR spectrum. Ultimately, the integration of XR support in invasive medical procedures leads to enhanced accuracy, improved safety, and transformative advancements in patient care.

1.2 Related Work

1.2.1 XR in Medical Procedures

The affordability of XR technology has sparked its widespread adoption across various medical settings, including planning, training, and execution of medical procedures.

In the medical education field, studies have shown that VR training outperforms traditional methods of learning anatomy, procedural skills, surgical procedures, communication skills, and clinical decision-making (161; 99). For example, an early comparative study involving 57 students investigated the educational effectiveness of a computer-generated 3D model depicting the middle and inner ear, resulting in impressive 18% improvements (121). In a more recent study, the use of VR training was found to enhance cadaveric temporal bone dissection performance by an impressive 35% when compared to traditional teaching methods (191). As VR enables simulation-based medical training that offers a safe experience for trainees to perform deliberate practice, it has increasingly been embraced in the realm of patient-based procedures (56; 145).

This includes applications in dental and bone surgery (15), minimally invasive surgery (55), and endoscopy training (80), where the use of virtual reality technology has gained acceptance.

1.2.2 The Acupuncture Training and Treatment Process

Traditional acupuncture, a TCM practice dating back thousands of years, is founded on the principles of the Meridian Theory (162), as outlined in the ancient text *The Yellow Emperor's Classic of Internal Medicine* (169). The two key concepts of this theory are meridian and acupuncture points (or acupoints). Meridian is a network of energy pathways that run throughout the body, where the life energy (called *qi*) flows. Acupoints are the specific points lying on the meridian where the *qi* converges and transfers. Acupuncturists in ancient times healed patients through the proper stimulation of acupoints.

Adapted from traditional acupuncture, current Medical Acupuncture (174) incorporates knowledge of anatomy, physiology, pathology, and the principles of EBM. Despite the unclear link between TCM acupoints-meridians and gross anatomy, the WHO standard (175) uses modern anatomical terms to describe acupoints and meridians. Nowadays, medical acupuncturists often work closely with other healthcare providers to provide integrated care. This integration of Western and Eastern practices has allowed practitioners to develop new and effective treatment methods that target anatomical structures and nerve pathways directly to produce specific physiological effects, such as reducing pain or stimulating the immune system (174). Accordingly, innovative acupuncture modalities arose, such as scalp acupuncture (59), eye acupuncture (150), auricular acupuncture (173), and wrist acupuncture (194).

A typical acupuncture treatment begins with an initial consultation and physical examination, during which the practitioner assesses the patient's health history, current symptoms, and overall situation. The practitioner then inserts thin needles into specific points on the patient's body to elicit the patient's sensation (called "de qi"). The practitioner may further provide recommendations for self-care or follow-up appointments and adjust the treatment plan as necessary. Using needles to stimulate specific anatomic sites is the core step in the treatment.

Strategic needle insertion into specific anatomic sites is a crucial component of acupuncture treatment. Although generally considered safe, even slight inaccuracies during needling can lead to unintended bleeding or organ puncture (171). As a result, novice practitioners may struggle to locate and insert needles correctly, potentially resulting in ineffectiveness or harm to patients. Further, individual differences in anatomy and sensitivity to stimulation can make precise needling more challenging (100).

In terms of acupuncture training, traditional acupuncture training often relies on two-dimensional models, pictures, or auxiliary teaching aids to demonstrate the position of acupoints. This approach lacks details, intuitiveness, and accuracy, introducing significant cognitive load in the learning process (54). To address these challenges, researchers combined medical anatomy education in VR and acupuncture knowledge to create a virtual three-dimensional space for teaching acupuncture (28). This allows beginners to visualize the anatomical structure of acupoints, realistically simulate the acupuncture process, and provide a safe foundation to enhance clinical efficacy. For example, a teaching experiment at the Guangzhou University of Traditional Chinese Medicine utilized a virtual acupuncture teaching system to display meridian outlines and anatomical details of key acupoints (138). One notable company that focuses on making VR solutions for general medical training experience is MAI (108). In 2021, their AcuMap (107) was the first commercialized acupuncture VR training system that incorporates anatomy, meridians, and acupoints on the standard 3D human model. Another trend in VR acupuncture research enables novice practitioners to localize acupoints on individuals with technologies including gesture recognition (188), face alignment (185; 187), and full-body tracking (39) to adapt to anatomical variations.

1.2.3 Integration of Medical Imaging in XR

Medical imaging plays a critical role in modern healthcare in both educational and non-educational contexts. Advanced visualization of medical imaging has become a significant area of research. The prevalence of 2D screens in DICOM viewers facilitates easy viewing of

medical images. However, this approach poses challenges for clinical practitioners and students in extracting crucial 3D information, including anatomical structures, regions of interest, and spatial relationships. Today, there are many advanced DICOM viewer systems available that offer 3D volumetric visualization. These systems provide users with a more comprehensive view of imaging data, and they can be accessed on both desktop (157; 129) and mobile platforms (127; 132).

XR takes medical imaging visualization to the next level by creating immersive and interactive experiences. By integrating XR into medical imaging education, students can explore realistic complex or subtle anatomy (111) and engage in hands-on training simulations. While non-educational virtual reality in particular is being increasingly used for two main scenarios: highly realistic simulators and highly interactive medical data visualization stations (130). A wide range of XR solutions already exist, integrating medical imaging with XR head-mounted displays. These solutions serve various purposes, including the general visualization of patient-specific 3D data volumes and models (140; 182; 154). Additionally, there are specialized applications designed specifically for surgical planning (159), simulation training (141; 56), and radiation oncology (67; 27), offering enhanced visualization and training experiences.

In the context of acupuncture, medical imaging not only aids in accurate localization of acupoints but also helps in understanding the mechanisms of acupuncture and its effects on the body (49). By incorporating medical imaging into acupuncture research and practice, researchers and practitioners can visualize and study the intricate relationships between acupoints, nerves, blood vessels, and other anatomical features (83; 81; 82). This integration promotes a more rigorous and scientific approach to acupuncture, strengthening its position as a viable therapeutic option within evidence-based medicine. For example, recent research in Harvard Medical School integrates meta-analysis, resting-state functional connectivity, and diffusion tensor imaging (DTI) to identify potential locations of scalp acupuncture for treatment of dementia (23).

1.2.4 3D Interaction in XR

3D selection in mid-air is commonly used in XR applications (12). Although advancements in hand tracking have improved accuracy and minimized the impact of object occlusion, interacting with far away objects and dense object selection still create problems in terms of user fatigue (70). Usually, using a 2D plane selection eases fatigue when the selection plane is within a small, easily reachable range. Interacting with objects in a Mixed Reality environment with a mobile phone has gained increased attention regarding its availability, familiarity, and social acceptance (22). Researchers see the potential to make it a control device for VR, AR, and XR settings with HMDs. The idea of tuning smartphones into input devices for HMDs attracted the designers' interest in various interactions. Karan et al. (78) enhanced the AR game experience by creating new interaction methods through a smartphone used as a game controller. Their remote input SDK makes connections between Unity applications developed for XR devices. Buschel et al. (22) contributes an exploration of smartphone-based interaction techniques for 3D pan and zoom, which are two essential tasks in HMD applications. They designed five 2D touch screen gestures mapped to pan & zoom operations in 3D. MARVIS (91) combines smartphones and HMD AR for data analysis. Their example use cases are primarily on top of the table, making the interaction on either table-top or mobile devices reasonable. Until now, few medical imaging-based surgical planning solutions on the HoloLens take full advantage of the flexibilities of the native engine. Our system builds on previous work, exploring the best rendering and interaction implementation on HoloLens 2 with comparably similar functionalities as on cell phones.

Chapter 2

CalAR: A C++ Engine for Augmented Reality Applications on Android Mobile Devices

2.1 Abstract

With the development of Apple's ARKit and Google's ARCore, mobile augmented reality (AR) applications have become much more popular. For Android devices, ARCore provides basic motion tracking and environmental understanding. However, with current software frameworks, it can be difficult to create an AR application from the ground up. Our solution is CalAR, which is a lightweight, open-source software environment to develop AR applications for Android devices while giving the programmer full control over the phone's resources. With CalAR, the programmer can create markerless AR applications which run at 60 frames per second on Android smartphones. These applications can include more complex environment understanding, physical simulation, user interaction with virtual objects, and interaction between virtual objects and objects in the physical environment. With CalAR being based on CalVR, which is our multi-platform virtual reality software engine, it is possible to port CalVR applications to an AR environment on Android phones with minimal effort. We demonstrate this with the example of a spatial visualization application.

2.2 Introduction

Recent advancements in mobile hardware and single camera-based tracking technology enable us to utilize augmented reality (AR) technology on mobile devices powered by Google's ARCore or Apple's ARKit software libraries. On Android devices, ARCore provides the functionality needed to use the Android phone for AR applications: camera-based six degrees of freedom (i.e., 3D position and 3D orientation) motion tracking, as well as the recognition of flat surfaces in the physical environment. The latter can be used to place virtual objects which snap to surfaces in the physical environment. Our aim was to build a lightweight, open-source software framework to easily and quickly develop AR applications for Android smartphones. Our framework includes 3D tracking and simple environment understanding. We also integrated a physics engine (Nvidia's PhysX), and implemented a lighting estimation module to illuminate the virtual objects in the scene as if they were illuminated by the light sources in the physical environment.

One of the most difficult aspects of creating AR applications for smartphones is to create appropriate techniques for intuitive interaction between the user and the AR application. The mobile nature of smartphone AR limits the user's interaction capabilities because a 3D controller or hand tracking is not generally available. We created an interaction system, which is based on finger taps on the smartphone's display, and gives access to the advanced 3D menu system from our virtual reality (VR) development environment CalVR, which CalAR is based on. This way the programmer can quickly add menu functionality which can be accessed through the smartphone's touch screen.

This article describes each component of the software system we built and summarizes our experiences with two demonstration applications we created with CalAR.

2.3 Related Work

In the early days of augmented reality applications on smartphones, fiducial markers located in the physical environment were used to estimate the phone's 3D pose with respect to the environment. One of the earliest software libraries which solved this problem was ARToolkit (3; 65), which used square, black and white markers similar to QR codes. Later on, the Vuforia library (5) allowed using known images of any kind for 3D markers.

Later on, miniature 3D accelerometers and gyroscopes became widespread sensors in smartphones, and researchers found ways to use them to improve position and orientation tracking. Ben Butchart's report on AR for Smartphones (6) provides an excellent overview of the state of the art in 2011.

Today, the most common approach for AR on smartphones is to use Unity (4) along with ARKit (2) or ARCore (1) to enable AR features such as 3D pose estimation and surface recognition. The reason why we developed CalAR is that it is fully open source (Unity is closed source), allows programming in C++, and is an extension of CalVR, which with its 10 year history has produced many VR applications which are desirable to run on a mobile device.

2.4 System Overview

CalAR is a software framework for Android to create augmented reality applications. Fig. 2.1 shows an overview of the system's software structure and its dependencies.

CalAR is targeted for Android while using the Java Native Interface to support its parent software CalVR's C++ code. With the use of ARCore, this system requires Android 7.0 (API level 24) or later. To take full advantage of CalAR, Android 8.0 (API level 26) or later is required. For rendering, GLES 3.x is supported starting from Android 5.0 (API level 21). More powerful graphics chipsets will increase the rendering rate, produce more fluid screen updates, and an overall better user experience. AR is very CPU and GPU-intensive.

For development and testing, we used a Samsung Galaxy S9 smartphone with Qual-

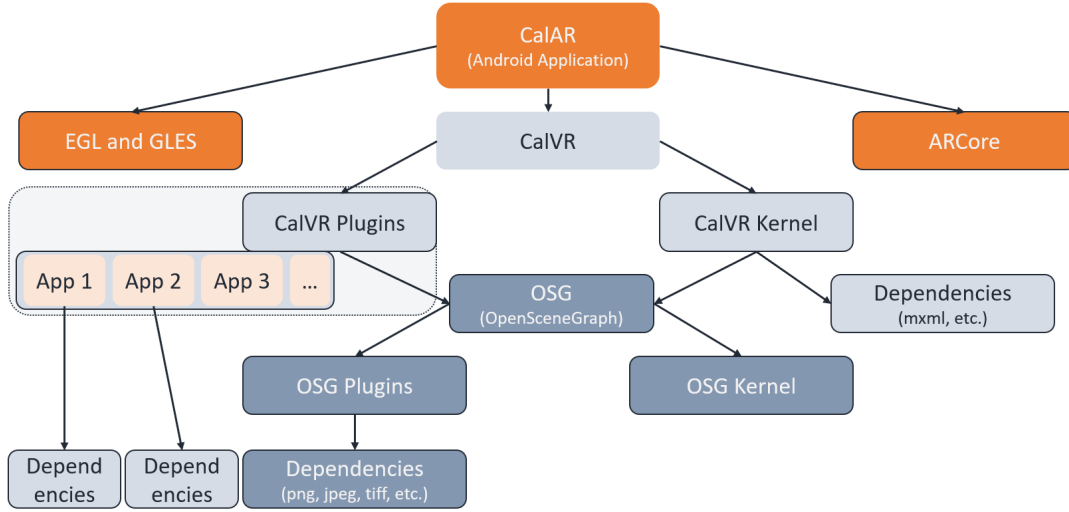


Figure 2.1. Software structure and dependencies of CalAR.

comm’s Snapdragon 845 SoC and an Adreno 630 GPU running at 710 MHz, API level 26. CalAR is the AR extension of our virtual reality visualization framework CalVR(149). CalVR is an open-source software framework written in C++ which implements VR middleware functionality for VR applications running on consumer VR headsets all the way to VR CAVES with large rendering clusters. CalAR extends it with AR pose estimation through ARCore, a physics engine, a 3D interaction concept for touch screens, and environment-based lighting.

2.4.1 Android-CalVR Communication

Communication between the high-level Android application and the low-level CalVR framework required a multi-layer software implementation. We use the Java Native Interface (JNI) for the main Android application, which is written in Java, to be able to communicate with the underlying C++ code from CalVR. We implemented an entry controller class as the jumping-off point into C++ where we can communicate directly with the various C++ libraries which are part of CalVR.

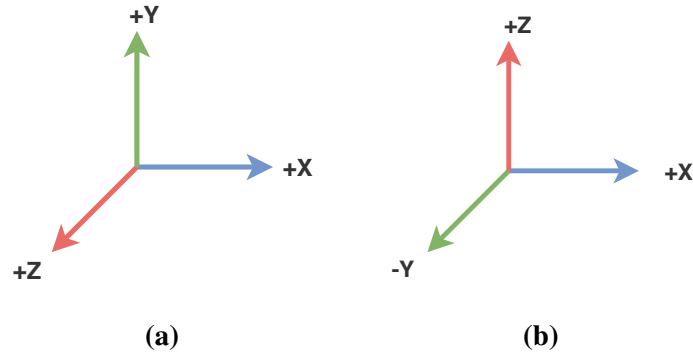


Figure 2.2. Aligning different systems: (a) tracking coordinates and (b) virtual coordinates.

2.4.2 3D Position and Orientation Tracking

Google’s ARCore has the ability to track a few dozen feature points in 3D using the smartphone’s built-in camera and motion sensors, and compute the 6-degree of freedom (DOF) trajectory of the device. The tracking system of ARCore is based on sparse feature detection. Once the 3D feature points are detected, and when the camera pose is known, we can overlay 3D virtual content on top of the image. ARCore’s tracking system is able to detect flat surfaces within a scene with rich features. Using ARCore as the backbone, we built our own tracking system aligning the real and virtual cameras as well as a variety of coordinate systems needed for application development.

Coordinate Alignment

The first issue we needed to tackle was the inconsistency of the coordinate systems between the virtual world and the real world. The tracking, or real-world system utilized a Y-up right-handed coordinate system, whereas the virtual system was a Z-up right-handed coordinate system. Fig. 2.2 shows the different coordinate systems for tracking (real-world) systems and virtual systems. The same issue arose when we integrated the physics simulation engine PhysX, OpenSceneGraph, and GLES. It is crucial for CalAR to work correctly so that the coordinate system transformation matrices for all coordinate systems are known.

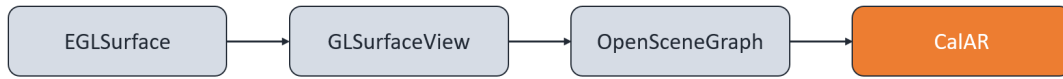


Figure 2.3. Rendering hierarchy.

Camera Alignment

ARCore creates the world coordinate system with the camera in its origin. As long as the system does not lose tracking, all detected feature and anchor points remain consistent. In a first person game for a regular computer, the user controls the behavior of the player character in the scene, which manipulates the virtual camera. However, since CalAR displays the real-world as seen by the camera held by the user, the viewpoint of the virtual scene should be aligned with this camera.

2.4.3 Rendering and Display

Android provides a system-level graphics architecture that can be used by the application framework. So we focused on how the visual data moves through the system based on Android's graphics architecture. Fig. 2.3 shows CalAR's rendering hierarchy. The low-level component EGLSurface is provided by Android. It is a graphics-rendering API that is designed to be combined with EGL (i.e., OpenGL ES). Using EGL calls, we can create and access windows through the operating system to render our scene. GLSurfaceView provides a helper class to manage EGL contexts, inter-thread communication, and interaction with the Activity lifecycle.

After creating and configuring a renderer to GLSurfaceview, we can then manipulate the GL context on both the Java and native C++ sides. CalVR utilizes the high-level graphics toolkit OpenSceneGraph (OSG), written entirely in Standard C++ and OpenGL, which enables us to write OpenGL code and GLSL shader files and adapt them as part of the scene structure.

Table 2.1. Map of multi-touch events to mouse events

Operation	Desktop	Mobile
Drag	Left click and move	One finger touch and move
Click	Left single click	One finger single tap
Double-click	Left double click	One finger double tap
Right-click	Right single click	Two finger single tap
Right-double-click	Right double click	Two finger double taps

Table 2.2. Unique events for touchscreen

Operation	Description
Long press	1, 2, and 3 fingers touch for an extended time
Fling	Single finger quickly swiping across screen

2.4.4 User-Interaction Interface System

In most cases, for handheld AR applications, the non-dominant hand holds the device and points the camera toward the target. Leaving the dominant hand free to interact with the virtual environment. We applied three interaction techniques to our interaction system: multi-touch, 3D direct touch, and a ray-casting manipulator for menu interaction.

Multi-Touch Interaction

CalAR being the AR extension of CalVR, is ready to use 3D controllers for user interaction, or mouse clicks on a regular monitor. But it is not prepared to interact through a touch screen with finger gestures. To translate mouse and 3D controller interactions into something more intuitive for touchscreen devices, we use multi-touch input from the touchscreen. The core mouse or controller events of clicking and dragging were mapped to multi-touch events. Swipes are interpreted as mouse drags, and taps are interpreted as mouse clicks, one finger corresponding to the left mouse button, and two fingers corresponding to the right. A breakdown of this can be seen Tab. 2.1.

In addition to providing this core functionality, we extended the interaction options to include multi-touch events that are unique to touchscreens, as well as long presses and flicks. Tab. 2.2 describes the unique events detected by our multi-touch detector.

3D Direct Touch

Mouse events, like clicking and dragging, can be more intuitive than multi-finger interactions. Often the latter interaction type requires prior knowledge to be able to correctly use the touch gestures. In an effort to make the interaction as intuitive as possible, we created the ability to touch and directly interact with the objects in the AR environment on the screen.

Object selection: ARCore detects feature points in the scene that describes the camera's position and orientation in world coordinates. We attach the virtual objects to the coordinate system these anchor points are in to ensure that they maintain consistent positions and orientations. Then to select a virtual object, the user simply touches the screen where the object appears. This touch triggers a virtual ray to be cast into the environment which then determines which object the user selected.

The initial touch position p_t is in 2D screen coordinates, and is first back-projected onto the near and far planes of the virtual camera's view frustum, as $\mathbf{P}_{t_{\text{near}}}$ and $\mathbf{P}_{t_{\text{far}}}$. This ray $\mathbf{P}_r$ can be represented by Equ. 2.1, where the scalar t is determined by the first object that the ray hits.

$$\mathbf{P}_r = \mathbf{P}_{t_{\text{near}}} + \mathbf{r} \cdot t, \quad \mathbf{r} = \mathbf{P}_{t_{\text{far}}} - \mathbf{P}_{t_{\text{near}}} \quad (2.1)$$

Object Translation: If we selected an object and want to move it within our scene, we click on the object to select it and drag our finger across the screen. When we dragged our finger the touch position changed from $\mathbf{p}_{t_1}$ to $\mathbf{p}_{t_2}$. These screen space vectors can be back-projected into 3D space as $\mathbf{P}_{r_1}, \mathbf{P}_{r_2}$. The scalar value t for $\mathbf{P}_{r_2}$ can then be calculated from similar triangles using Equ. 2.2, where $\mathbf{n}$ is the normal vector of camera plane:

$$t = \frac{\mathbf{n} \cdot \mathbf{P}_{r_1} - \mathbf{n} \cdot \mathbf{P}_{t_{2\text{near}}}}{\mathbf{n} \cdot \mathbf{r}} \quad (2.2)$$

Object Rotation: We handle 3D rotations similar to translations. In order to rotate an object we first click on the object to select it, then drag our finger to rotate the object. Our rotations

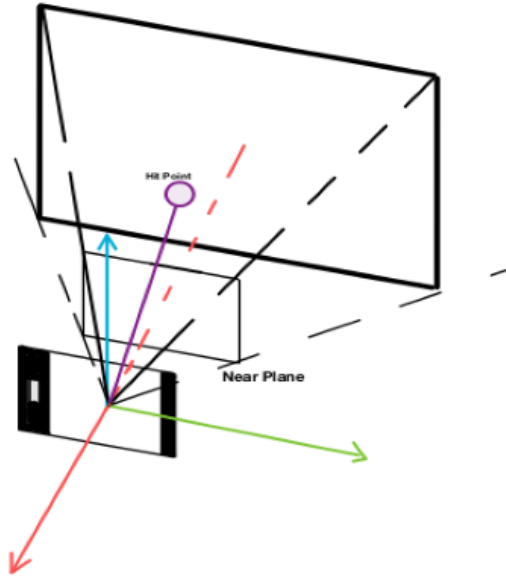


Figure 2.4. Ray-object intersection test in 3D space.

are about the X and Y axes of the camera coordinates, and the angle is based on the difference between the previous and current touch positions, $\mathbf{p}_{t_1}$ to $\mathbf{p}_{t_2}$.

$$\mathbf{R} = \text{Angle_Axis}(\delta_x, \text{Axis}_Z) \cdot \text{Angle_Axis}(\delta_y, \text{Axis}_X) \quad (2.3)$$

$$(\delta_x, \delta_y) = p_{t_2} - p_{t_1}$$

Ray-casting Manipulator

CalAR's menu system is an extension of CalVR's menu system. After a designated tap event occurs, the menu is placed facing the user inside the 3D environment. We then recreate the effect of a mouse cursor with a ray-casting manipulator. The ray starts at the camera position and extends into the scene. This manipulator is drawn in the scene as an orange line segment. For each frame, we check the intersection between the stroke and the menu and highlight the potential menu selection. Selecting this menu item is done by tapping the main button seen at the bottom of the screen, which always remains visible. Screenshots of this interaction are shown in Fig. 2.5a

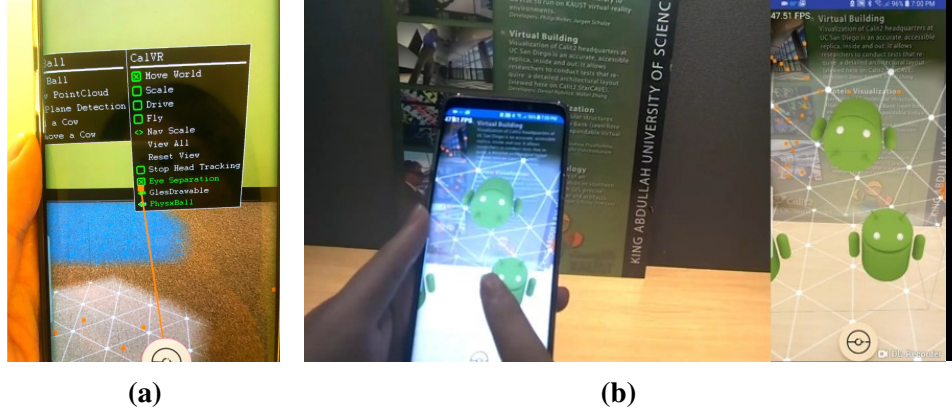


Figure 2.5. 3D User Interaction: (a) ray-casting method, and (b) 3D direct touch to place Android robots.

We designed this ray-casting manipulator to avoid “fat finger” errors (151) and enable precise selection. We noticed that it could be difficult to interact with the menu, so we created this ray-casting function to allow the user to more clearly see what menu option they are clicking on. We also use this ray-casting method to manipulate the menu placement. By selecting the top of the menu with the ray the menu attaches to the ray, and by moving the phone the user can move the menu around the scene. We then created this method of interaction as an alternative to the 3D Direct Touch method. The advantage of the new method is that it does not limit the manipulation of the virtual objects to the size of the mobile device’s screen.

2.4.5 Physics Engine

To demonstrate how real-world data from the environment can be incorporated within an augmented scene, we integrated PhysX, Nvidia’s multi-platform physics engine, into our software framework. Since we use the latest NDK, in order to prevent linking and runtime errors due to combining libraries built by different compilers and standards, we updated PhysX’s Android makefile to build PhysX with the latest NDK with Clang instead of GCC, and statically linked all PhysX libraries. PhysX maintains and runs simulations inside its own PhysX world, so we dynamically update real-world data coming from ARCore into the PhysX scene. Whenever

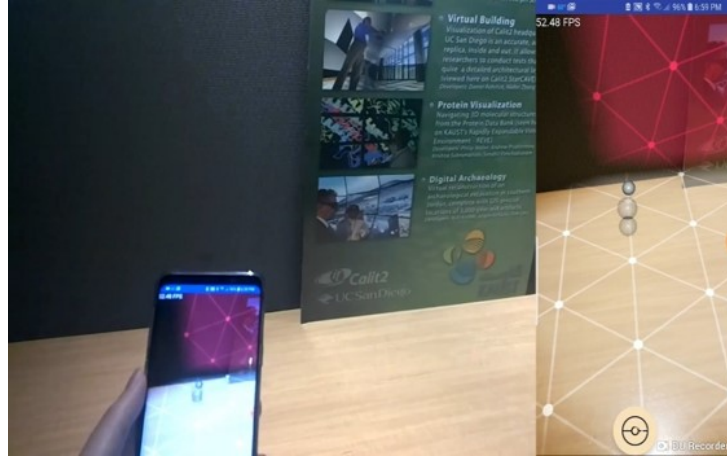


Figure 2.6. A ball thrown on the plane bounces off it.

ARCore detects a flat surface or plane in the environment, we create a thin box to tightly fit the detected plane. We found that this reduced the performance cost when compared to dynamically updating a convex mesh into the PhysX scene. Fig. 2.6 shows a bouncing ball example of this feature.

2.4.6 Lighting

We implemented three different approaches for lighting in our Android app: ARCore Native, Single Source, and Spherical Harmonics. In our demo application, the user can select on a per-object basis which of the three lighting methods to use, which allows rendering different objects with different lighting methods in the same scene and directly comparing them to one another.

ARCore Native

AR Core Native comes directly from ARCore. This method calculates the average pixel intensity of the captured image, and renders the objects based on that average brightness. This is our lighting baseline to compare other lighting estimation implementations.

Single Source

Single Source builds on the functionality available in ARCore to improve the lighting of the scene. We calculate the pixel location of the brightest point in the captured image. This is then used as a 3D point light to provide additional lighting to help create a more realistic rendering for diffuse and specular surfaces.

Spherical Harmonics

Spherical Harmonics lighting projects objects and/or environment map into spherical harmonics frequency space, and then calculates lighting with spherical functions (136). By pre-computing the complex lighting environment and per-vertex radiance transfer function into vectors of coefficients in frequency space, the lighting integration can be done in real-time. This method relies heavily on a detected environment map, so we implemented two ways to iteratively build this environment map. As the user uses the AR app and points the smartphone in different directions, we gather more and more images and create a more complete environment map.

1. We use OpenCV to stitch the input images into a panoramic image. This method is slow but accurate.
2. We use projection and view matrix from ARCore to directly project the image onto a sphere. This method has a smaller performance impact, but tends to be more inaccurate in a more confined environment.

These methods are only applied once every 50 rendered frames (about once per second) so that they do not slow down the rest of the application too much. Initially, we only use the current view as the environment map, assuming that the rest of the environment does not contribute to the augmented scene yet. Once we were able to stitch together enough images to fill at least 80% of the environment map we switch to the more complete environment map to make sure we use information in the calculations that will result in more accurate rendering.

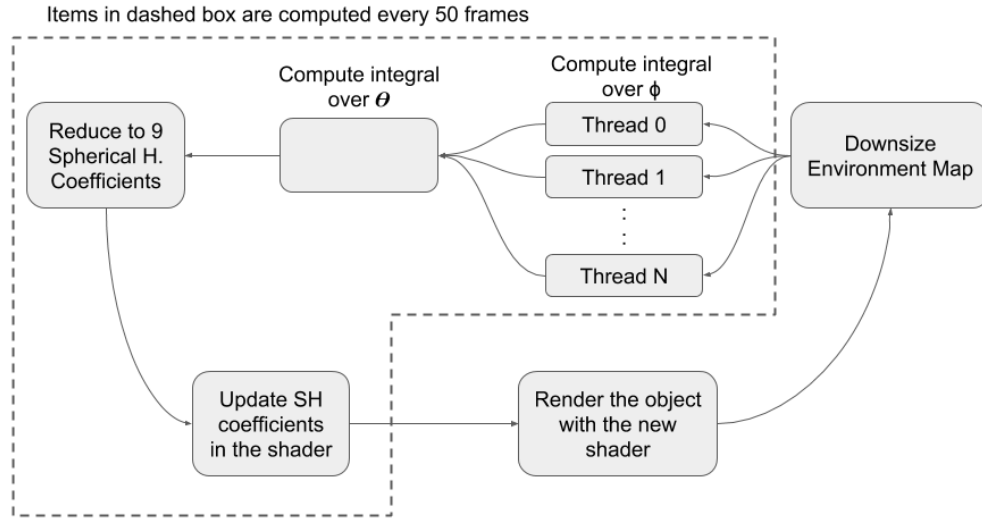


Figure 2.7. Showing the flow of the Spherical Harmonics algorithm used within the Android app. The Spherical Harmonics are only calculated and updated every 50 frames.

To compute the Spherical Harmonics on this environment map we downsize the image, and the following calculations are completed every 50 frames:

- We compute the integral of the environment over one dimension ϕ . This calculation is parallelized and completed in multiple threads.
- Once this is complete, one thread then computes the resulting 9 Spherical Harmonic coefficients by integrating over the other angle θ .

In every frame these Spherical Harmonic coefficients are sent to a shader to calculate the diffuse colors and render objects based on the current environment map. The flow of the Spherical Harmonics Algorithm can be seen in Fig. 2.7.

2.5 Test Applications

We created two plugins to demonstrate the features of our CalAR system. The first one *Play with Android Andy* demonstrates the following features: basic rendering, interaction,

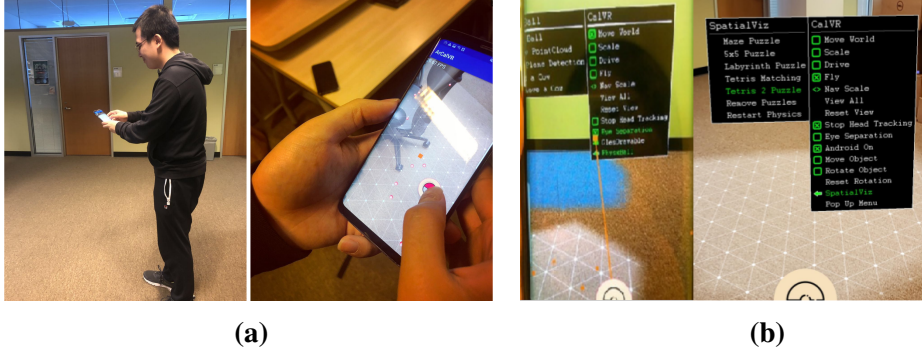


Figure 2.8. 3D User Interaction: (a) ray-casting method, and (b) 3D direct touch to place Android robots.

physics, and lighting. The other, *SpatialViz*, is an application originally developed as a CalVR plugin for VR environments. We adapted it to our CalAR in Android to show the abilities to build, use, and integrate plugins that were developed for CalVR.

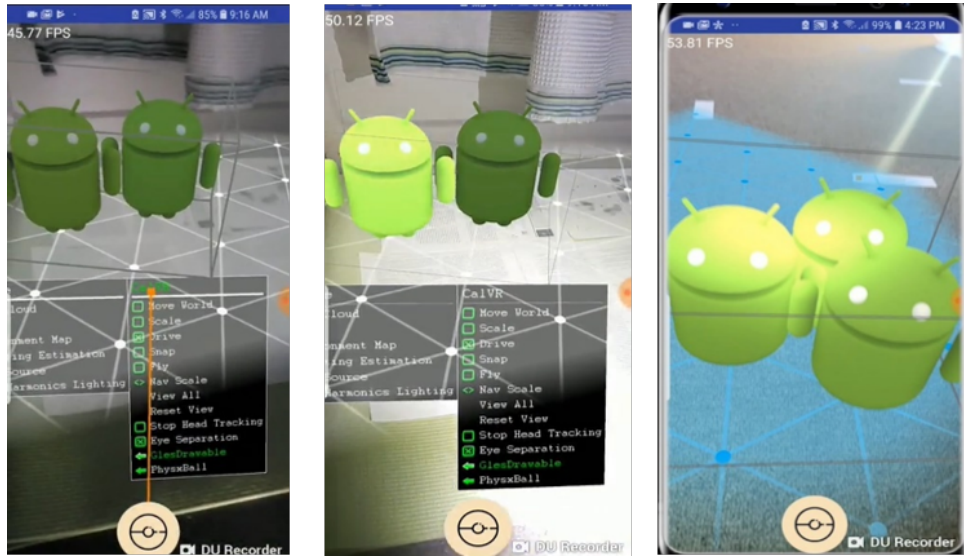


Figure 2.9. Three lighting modes: baseline, Spherical Harmonics lighting + baseline, and single light source.

2.5.1 Demo App: Playing with Android Robots

This application is shown in Fig. 2.8a. To start the app, the user holds the phone up and sees the 3D menus shown in the physical environment. Then he double-taps the screen and the main menu pops up in front of him (Fig. 2.8b). After browsing the menu, he points the ray to

check the box “Add an Andy” with the default lighting mode. With the camera facing the floor, a flat surface is drawn on the screen in the location of the floor, and Android robots can be placed on this surface. To interact with them the user places robots in random positions and rotates one of them to face the others, see Fig. 2.5b.

We also implemented three different lighting modes as shown in Fig. 2.9. The single-source-lighting estimates the real-world light source and the Android robot shows a highlighted spot on its head. Spherical Harmonics lighting mode, on the other hand, captures the current view of every 50th frame and stitches them iteratively to generate a panoramic image of the environment (see Fig. 2.10).

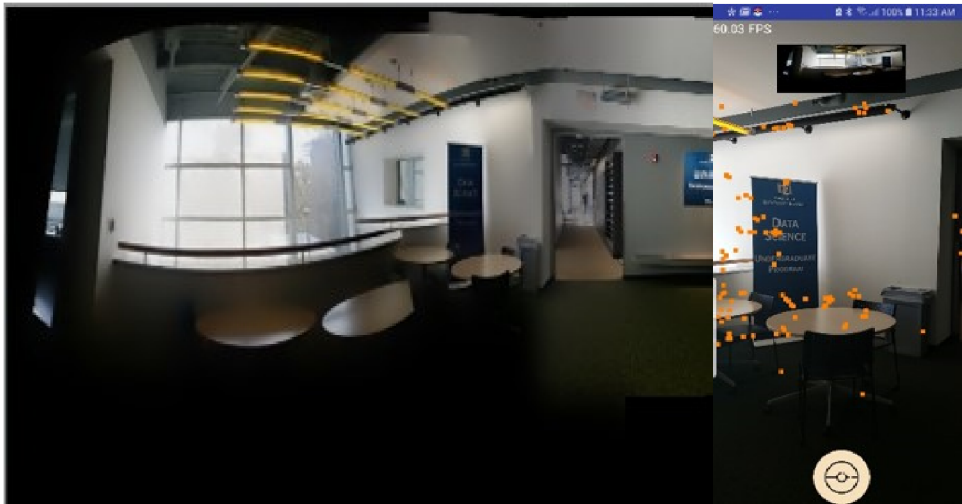


Figure 2.10. Creating a panoramic image iteratively from different viewing directions.

2.5.2 Demo App: Spatial Visualization Trainer

Our pre-existing Linux-based spatial visualization training application for CalVR was developed to teach engineering freshmen better 3D spatial visualization skills. The application uses a basic framework for 3D interaction within a VR environment. We thought that the spatial visualization trainer was a good, typical app to test how easy it would be to port a CalVR application to CalAR. This application also included a variety of components we wanted to test out in CalAR, such as PhysX, as well as 3D interaction with virtual objects.

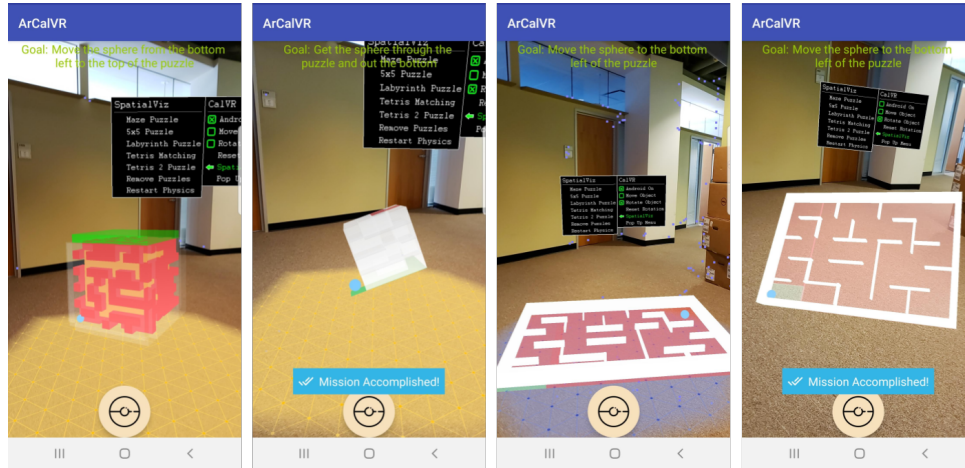


Figure 2.11. Showing three of the different puzzles created in the spatial visualization training app. Each involve the rotation and manipulation of different puzzle pieces to get the ball to go where it should.

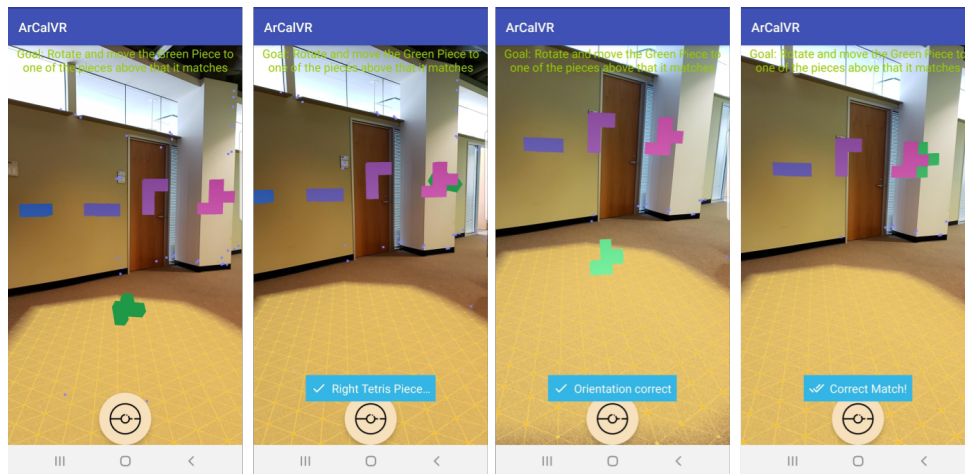


Figure 2.12. Tetris puzzle: the user needs to move and rotate the green puzzle piece in the AR space using taps and swipes to find and match the position and orientation of another piece.

The spatial visualization trainer creates virtual 3D puzzles that the user can interact with in 3D space. Fig. 2.11 shows three different puzzles created by the app. Each of them involves the use of the PhysX library to simulate the interaction between the puzzles and a ball. Android Toast-style messages are displayed to the users when they have completed the puzzle, made possible by two-way communication through the JNI and controller classes. Fig. 2.12 shows our 3D Tetris puzzle and the different messages displayed to the user.

2.5.3 Discussion

The porting of the spatial visualization trainer app from CalVR to CalAR showed us various parts of the software which needed to still get fixed. Once it worked, we tested it out among the developers and report on our observations below.

CalAR vs. CalVR

When we initially ran the CalVR plugin on the Android phone a big issue was the scale of virtual objects. CalVR is a VR-only platform and as a result, the scaling of objects can be fairly flexible. However, in our Android application, the camera position is fixed within the real world, so the scale of objects becomes fixed. We needed to re-scale the objects and address some floating point issues before the application ran smoothly. Fig. 2.13 shows a comparison between the Linux (CalVR) and Android (CalAR) environments for two of the puzzles in the trainer application.

Real World Coordinates

ARCore is able to detect flat surfaces within a scene if there are enough features on the surface, i.e., if you are looking at a flat solid colored wall ARCore may not detect that surface. Once ARCore does detect a flat surface, ARCore can project a 2D screen tap into a 3D feature point onto that surface. So the functionality we ended up implementing was that when a surface was detected, a single-finger double-tap would then be translated into that World Coordinate feature point. The matrix that describes the translation and rotation of that feature point could then be used to place our application's objects onto the surface.

One thing that we always had to be cautious of was the units and orientation of the coordinate system. We were dealing with a lot of different coordinate systems and ensuring that they all correctly lined up was a recurring issue.

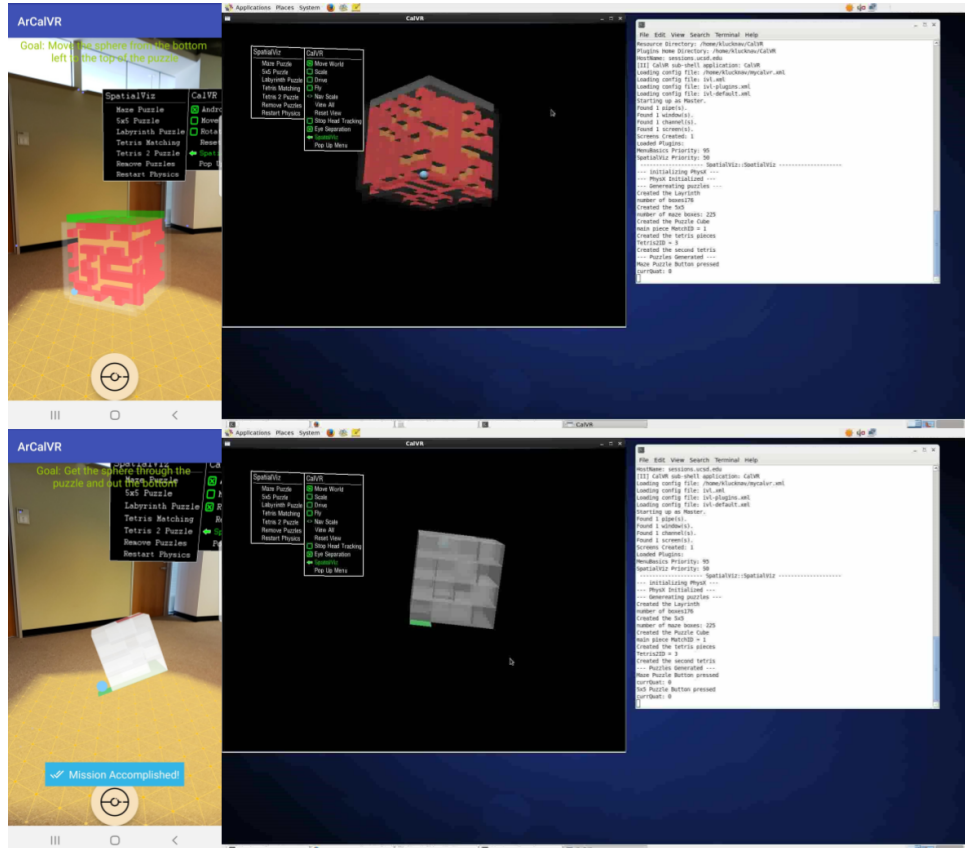


Figure 2.13. Comparison of the Linux and Android environments running the spatial visualization trainer app.

Camera Positioning

The Linux-based system had a set initial camera position, and upon a mouse click and drag the camera position rotated around the stationary object. This type of interaction no longer made sense in an AR environment. We first fixed the camera location to the phone's camera location so it properly lined up with the real-world image on the screen. We then changed the click-and-drag interactions to change the object's position and orientation rather than the camera's.

Rendering Performance

The different puzzles were all created with boxes and spheres. As a result, the amount of triangles that needed to be rendered for the puzzles ranged from between 300 and 3,650 triangles.

CalAR was able to seamlessly render these puzzles while maintaining a frame rate of 60 frames per second.

2.6 Conclusions

Based on our existing CalVR middleware software, the new CalAR for Android integrates ARCore as the tracking system, as well as a 3D menu system, a physics engine, and environment-based lighting. With the CalAR framework, software developers can build their own AR applications more easily than starting from scratch. If all that is needed is an AR application for smartphones, Unity may often be the better answer. But if open source or compatibility with a wide range of VR systems is desired, CalAR offers a viable alternative.

2.7 Acknowledgments

This project was funded in part by Samsung Electronics and the Helmsley Charitable Trust.

Chapter 2, is largely a reprint of the material as it appears in Zhang, Menghe, Karen Lucknavalai, Weichen Liu, and Jürgen P. Schulze. “Calar: A c++ engine for augmented reality applications on android mobile devices.” *Electronic Imaging* 32 (2020): 1-7. The dissertation author was the primary investigator and author of this paper.

Chapter 3

Server-Aided 3D DICOM Image Stack Viewer for Android Devices

3.1 Abstract

Digital Imaging and Communications in Medicine (DICOM) is an international standard to transfer, store, retrieve, print, process, and display medical imaging information. It provides a standardized method to store medical images from many types of imaging devices. Typically, CT and MRI scans, which are composed of 2D slice images in DICOM format, can be inspected and analyzed with DICOM-compatible imaging software. Additionally, the DICOM format provides important information to assemble cross-sections into 3D volumetric datasets. Not many DICOM viewers are available for mobile platforms (smartphones and tablets), and most of them are 2D-based with limited functionality and user interaction. This chapter reports on our efforts to design and implement a volumetric 3D DICOM viewer for mobile devices with real-time rendering, interaction, a full transfer function editor and server access capabilities. 3D DICOM image sets, either loaded from the device or downloaded from a remote server, can be rendered at up to 60 fps on Android devices. By connecting to our server, users can a) get pre-computed image quality metrics and organ segmentation results, and b) share their experience and synchronize views with other users on different platforms.

3.2 Introduction

Magnetic resonance (MR) and computed tomography (CT) imaging devices have been incorporated into mainstream radiology practice and are performed daily for a wide range of clinical indications. DICOM datasets are widely used in the medical field. Traditionally, a radiologist reviews a patient's imaging data one 2D image at a time and selects those that show the best views of the disease among hundreds of images, using them as the basis for a medical report. More recently, 3D volumetric visualization offers a more comprehensive view of medical imaging data. However, volumetric visualization is more compute-intensive than 2D imaging, thus viewing systems must process data particularly efficiently, and due to the complex nature of volumetric data sets they must be user-friendly to be useful.

There are many applications on desktop platforms for different usage scenarios, some of which use novel methods that take the 3D information into account that is stored in the image sets. We decided to develop our software for mobile devices to balance convenience and performance. Recent advancements in mobile chipsets enable us to do complex rendering in real time. Our software makes 3D volume visualization more approachable for both specialists and non-specialists and the mobile nature of the devices makes it easier to communicate, for instance for doctors with their patients.

One problem we addressed is how to improve the 3D visualization of medical data by utilizing the available meta-data from the DICOM files. Another challenge was how to properly design the user interface to provide the necessary visualization features without overwhelming the user with too much complexity.

We developed an Android application to load, view and interact with 3D medical volumes (Fig. 3.1). We designed the core software modules to make it easy to support other hardware platforms. Some mobile DICOM Viewers provide access to hospital image servers (PACS) to retrieve datasets. We created a server running on a desktop, provides another option that lies in-between the mobile clients and remote PACS system so that we can store pre-processed

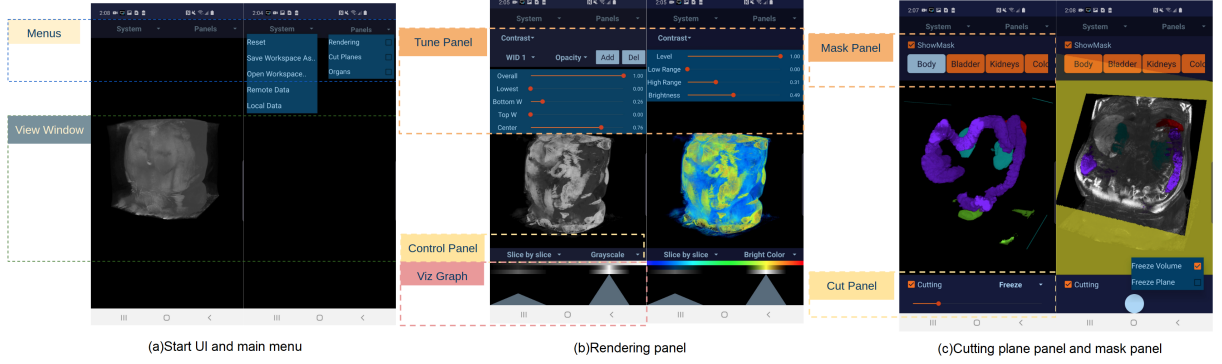


Figure 3.1. Demonstration of user interface design

MRI datasets and metadata, in order to minimize the computational load on the mobile device. Compared to previously existing DICOM viewers, the novel contributions of our work are:

- **Real-time experience:** Real-time volume rendering with a 2-stage process on mobile Android platforms.
- **Rich functionalities:** A client-server architecture which provides additional information including organ masks, colon center lines and image quality metrics. Those data allowed us to add features that are not found in other mobile medical data viewers.
- **Collaborative views:** Our server also provides the ability for users on different devices with different platforms (e.g., PC) can view the same data in the same exact way, to allow for cross-platform collaboration.

Potential use case scenarios for our applications are varied, for example, medical education, communication, surgical planning, and early disease detection.

3.3 Related Work

3.3.1 Volume Rendering

Volume rendering techniques, including direct and indirect rendering, have been developed for medical image visualization to create customizable images (128; 189). Direct Volume

Rendering (DVR) (98; 38) generates images of 3D volumes by using an optical model to map data values to optical properties, such as color and opacity (112). DVR includes backward and forward methods. Ray-casting is an example of backward methods, which is performed pixel-by-pixel. This method was introduced by Kajiya and Herzen (75) and was later translated to the GPU (88).

In the medical field, this rendering technique is used to transform sets of 2D images into 3D volumes. Some previous work optimizes the three steps for the unique needs of clinical use and sometimes aim to help anticipate potential complications during surgery operations (37; 72). For example, Fishman et al. (46) compared the popular methods of alpha blending and maximum intensity projection for the evaluation of CT angiographic data sets. These two techniques have different advantages and disadvantages when used in clinical practice, and it is important that radiologists understand when and how each method should be used.

3.3.2 DICOM Viewers

DICOM viewers are often developed with a focus on one or more of the following functions: 1) quick viewing of medical images; 2) browsing the images from PACS servers. Some offer 3D rendering features as an option. According to a survey of DICOM viewers in 2016 (57), products that provide great 3D imaging with a high reputation are ImageJ (144), MicroView (68), MIPAV (153), and OsiriX Lite (143). The recently released Horos for Mac is a free version of OsiriX, which is often considered the best DICOM viewer for Macs. Other software applications, like PostDICOM (133), Weasis (142), Ginkgo CADx, and Pro Surgical 3D allow high-quality rendering with high performance on PCs. In recent years, the web paradigm has introduced new visualization, sharing and interaction opportunities for medical images. Some web applications use WebGL to provide easy access to a quick 2D or 3D visualization of datasets (11; 8; 33), but 3D rendering performance cannot compete with native applications. In the mobile field, choices are more limited. Products on mobile devices like mRay (113), Symmetry (62), iPaxera (35) and simpleDICOM (20) provide a 2D view for each slice. Some of

them enable the connection to a PACS server but do not have ways to store and share datasets. DroidRender (156) is considered one of the best options on Android that provides a fully functional 2D and 3D render engine, tissue segmentation and slicing.

3.4 System Overview

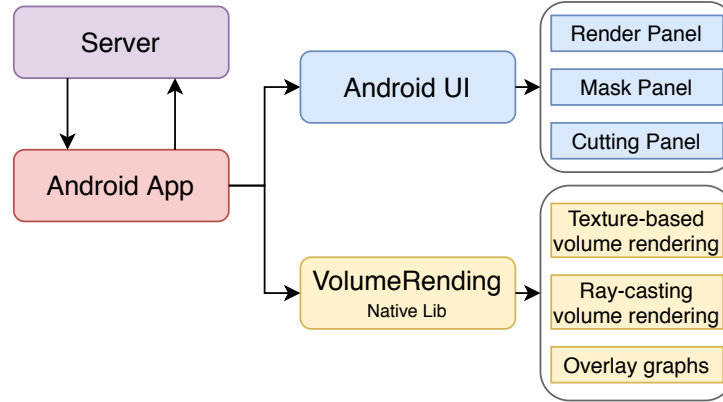


Figure 3.2. Software structure

Our software system consists of an Android app and an optional image server. Fig. 3.2 shows an overview of our application. It is targeted towards Android, using the Java Native Interface to implement all the core functionalities in C++ for greater speed. For development and testing, we used a Samsung Galaxy S10 smartphone with Qualcomm’s Snapdragon 855 SoC and Adreno 640 GPU, API level 28. More powerful graphics chipsets will increase the rendering rate, produce more fluid screen updates, and overall better user experience.

3.5 Volume Rendering and Display

We created a two-step rendering algorithm with a compute shader (Fig. 3.3). A 3D texture is prepared in stage one and rendered in the next stage. In stage one, the 3D texture is prepared with color and opacity mapping (transfer function), which are done in a compute shader. In stage two, this 3D volume is rendered with one of two methods: texture-based or ray-casting. This design separates the rendering parameters into two groups.

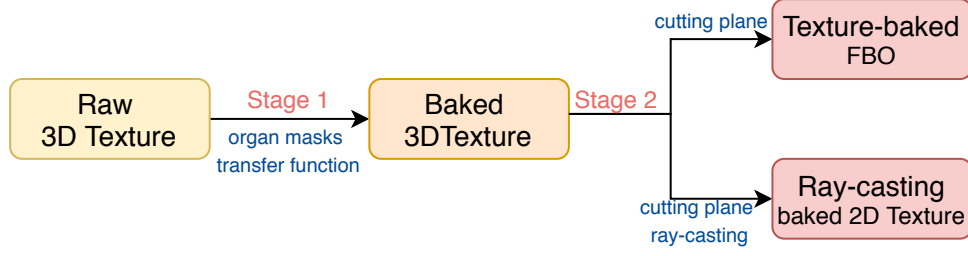


Figure 3.3. Illustration of our 2-stage rendering scheme

3.5.1 Stage One: Preparing the 3D Texture

For each volume data set, a 3-dimensional texture is created with data that is loaded gradually. Initially, users select a volume from the local or remote data set list, and the corresponding volume information is sent to the native application to allocate a buffer and prepare to set up 3D texturing. Once data loading finishes, the app creates a 3D texture and enters the second stage. At this point, additional data can still be assembled into the same buffer and sent to the GPU after all processes finish. In the compute shader, the following parameters are considered:

Organ Mask: Raw data in the texture represents 12 bits intensity values while each organ mask takes 1 bit for each unit of the texture (texel). So we create the texture in r32ui (red channel-32 bits-unsigned int type) format. The upper 16 bits are allocated for masks, and the lower 16 bits are for volume data. The system gets mask data asynchronously from the server and combines this part of the data with the intensity data and sends it to the GPU. We later assign each organ a unique color. Fig. 3.4 shows an abdominal MRI segmented into bladder, kidneys, colon, spleen, etc.

Transfer Function: We drew inspiration from the work of Chourasia et al. (32) to create effective intensity transfer functions for high dynamic range scalar volume data. Compared to their method, our work provides a 2-step approach: 1) a uniform enhancement of contrast and brightness; 2) simple primitives as widgets that allow users to design their own data opacity patterns. First, given a pair of contrast limits (C_{bottom}, C_{top}) and the brightness C_b , the value of each voxel C_x is enhanced as:

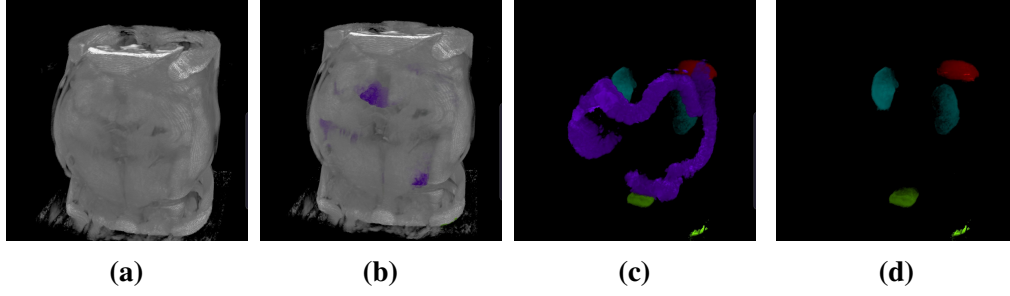


Figure 3.4. An abdominal MRI with organ segmentation: (a) no organ masks, (b) body and organs with organ masks, (c) organs only, and (d) kidneys and spleen only.

$$C_{t1} = (C_x - C_{bottom}) / (C_{top} - C_{bottom}) + C_b, \quad (3.1)$$

$$(C_{bottom} \leq C_x \leq C_{top})$$

Secondly, multiple opacity widgets can be applied to pull out specific parts of the volume. For each widget, there are 5 parameters ($v_o, v_l, vw_b, vw_t, v_c$) that determine the 6 control points (**lb, lm, lt, rb, rm, rt**) of the widget:

- Overall (v_o): the highest value of the opacity ($.0 \leq v_o \leq 1.0$).
- Lowest Bound (v_l): the lowest value ($.0 \leq v_l \leq v_o$).
- Top Width (vw_t): the top range value ($.0 \leq vw_t \leq 2.0$).
- Bottom Width (vw_b): the bottom range value ($vw_t \leq vw_b \leq 2.0$).
- Center (v_c): position of the highest value ($.0 \leq v_c \leq 1.0$).

Then the 6 control points can be calculated accordingly. When multiple widgets add up, with the first transfer function being C_{t1} , we get

$$C_{t2} = \max(\text{Widget}_i(C_{t1})), \text{ where } i = 1, 2, \dots, n \quad (3.2)$$

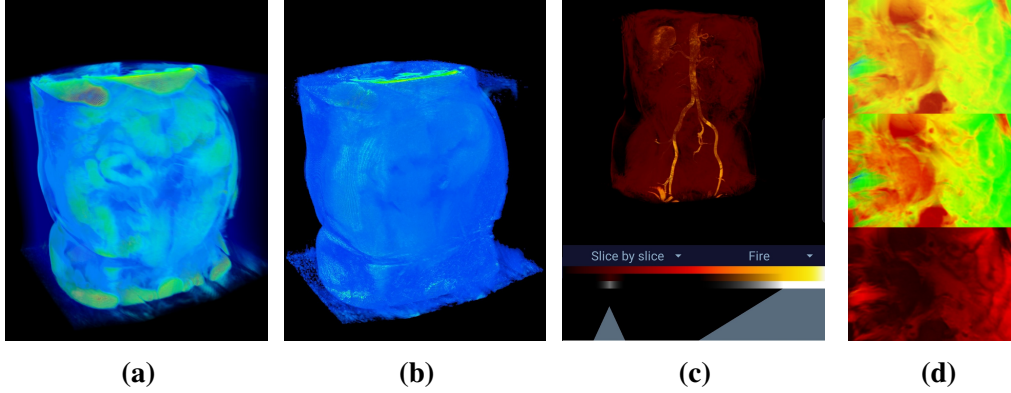


Figure 3.5. Volumetric Rendering with transfer function: (a) texture-based method rendering, (b) ray-casting method rendering, (c) an abdominal MRI with opacity widgets and the color transfer function graph, and (d) Tissue visualization under different color transfer scheme (HSV, fine-tuned HSV, and the Fire color scheme).

Fig. 3.5c demonstrates the visualization of a volume with opacity widget graphs and a color transfer function bar. Users can get an intuitive view of how the parameters affect the transfer functions and how they affect the volume visualization. We realized that the piecewise linear paths through RGB color space have two major issues. One of them is that the perceptual flat spots in the color map hide detailed features; the other is the perceptual discontinuities that induce false features. Fig. 3.5d shows a part of the volume rendered with the HSV color scheme. The clustering of points in the green and red regions produces perceptual flat spots in the color map, thus limiting the effects only by contrast enhancement and opacity adjustment. Also, yellow and red produce false anomalies seen at these spots. Therefore, we extend the color schemes with Fire and CET-L08 from Kovessi’s work (85), which uniform the magnitude of the incremental change in perceptual lightness. As also shown in Fig. 3.5d, the new color scheme performs better for detail perception.

3.5.2 Stage Two: Render the Volume

We use Direct Volume Rendering (DVR) to show the entire 3D data volume and provide the options of texture-based (forward) and ray-casting (backward) volume rendering.

The Texture-based Method projects each slice onto the viewing plane and blends

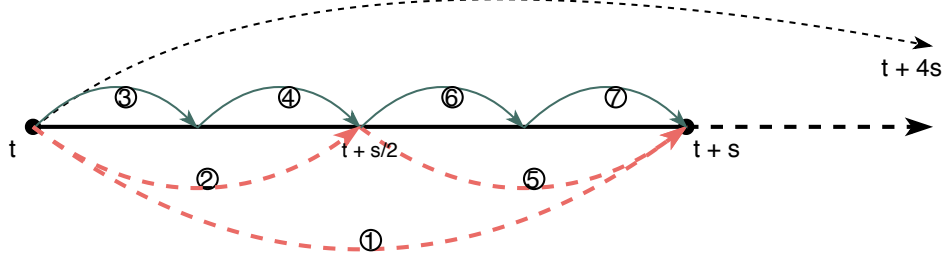


Figure 3.6. Illustration of adaptive sample steps

according to capacities. All texture-mapped slices are stored in a stack and are blended back-to-front onto the image plane, which results in a semitransparent view of the volume. We then align the slices in object space parallel to the Z-axis, representing the nature of a stack of 2D images (Fig. 3.5a). Therefore, viewers would look on the slice edges by rotating the volume and see through the stacked slices. By projecting the voxels of the slice plane on pixels of the viewing plane, a pixel can lie in-between voxels, so its value is from bilinear interpolation.

The Ray-casting Method casts a primary ray from the camera into the volume, sampling the volume in regular intervals (Fig. 3.5b). The final color and opacity of the pixel are accumulated along the ray (131) by:

$$C_{out} = C_{in}(1 - \alpha(x_i)) + C(x_i)\alpha(x_i) \quad (3.3)$$

Ray-casting with Adaptive Sampling Method we proposed takes more sampling steps in denser parts of the volume to enhance details. Algorithm 3.1 shows the pseudo-code of our adaptive sampling method. The goal is to perform the ray-casting from t to $t + s$.

input : $r_o, r_d, head, tail, s_u, thresh_terminate, thresh_ignore, thresh_init$

output : $color(r, g, b, a)$

$color \leftarrow 0; threshold \leftarrow thresh_init;$

for $t \leftarrow head$ **to** $tail$ **do**

if $color.a \geq thresh_terminate$ **then**

 | terminate;

end

$p \leftarrow r_o + r_d \times t;$

$sampler \leftarrow Sampling(p);$

if $sampler.a > thresh_ignore$ **then**

$contrib \leftarrow (1.0 - color.a) * sampler.a;$

if $contrib > threshold$ **then**

 | $s \leftarrow s/2; threshold \leftarrow \min(2 \times threshold, 1.0);$

 | $last_succeed = false;$

else

$color.rgb+ \leftarrow contrib \times sampler.rgb;$

$color.a+ \leftarrow contrib;$

$t \leftarrow t + s;$

if $last_succeed$ **then**

 | $s \leftarrow 2 \times s; threshold \leftarrow threshold/2$

else

 | $last_succeed = true$

end

end

else

 | $t = t + 4 \times s_u$

end

end

Algorithm 3.1: Accumulated ray-casting volume rendering with adaptive sampling step.

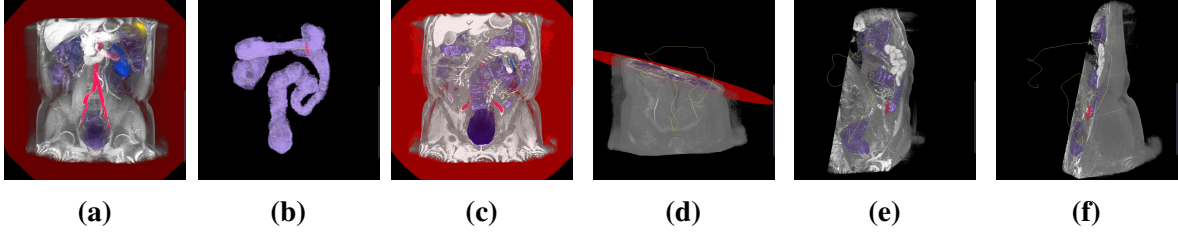


Figure 3.7. Cutting Planes in (a)(b) texture-based method, (c)(d) ray-casting method, and (e)(f) through colon's center line.

When sampled $\alpha_{channel} > 0.01$, we evaluate the alpha contribution from the current step: (1) If the contribution exceeds the threshold, we halve the step size and double the threshold and try to advance from t to $t + \frac{s}{2}$. (2) If the contribution is below the threshold, we accumulate color and alpha and adjust step size and threshold based on the test of the last step. Fig. 3.6 illustrates how this adaptive sampling during data accumulation is performed from t to $t + s$

3.5.3 Display Auxiliary Information

Besides the original data volume, our system provides auxiliary information that helps to improve the user's ability to get the best view of the data.

Cutting Plane: We implemented a GPU-based cutting plane to view details of a selected position with user interaction. In texture-based rendering mode, a volume is composited by stacking a set of slices together so that users can view the data volume slice by slice as they do traditionally. While in ray-casting rendering mode, users have more flexibility to uncover occluded details in any direction and any depth. Fig. 3.7a–3.7d show screenshots of a cutting plane with texture-based and ray-casting methods. Notice that in the ray-casting method, one can choose to keep the volume or cutting plane fixed in place and manipulate the other.

Organ Center Lines: The server generates center lines of the colon and ileum for selected datasets. We also extended the cutting plane to allow for traveling continuously along the center line (Fig.3.7e3.7f). By switching to the *cutting view*, the view direction will follow the center line to see through the cutting plane. In any view mode, users can always perform touch

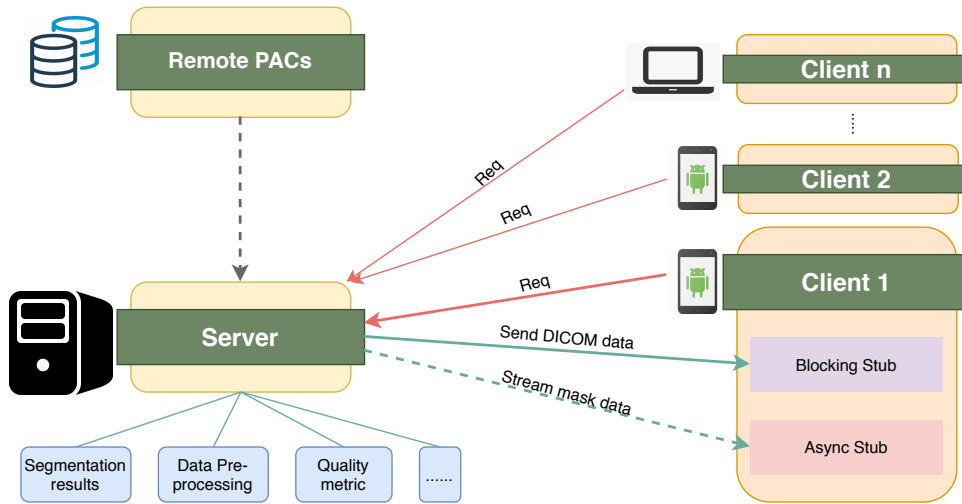


Figure 3.8. Server work flow

gestures to scale, rotate and move the data volume.

3.6 gRPC Server

The gRPC server we created runs on a desktop and provides another option that lies in-between the mobile clients and the remote image server (PACS system) that 1) stores and pre-processes MRI datasets to generate auxiliary information and 2) provides communication between multiple clients or between the server and one of the clients.

With gRPC, a client application can directly call a method on a server as if it were a local object. This process can be called synchronously and asynchronously with different types of stubs. According to our need to browse and request datasets, we created the workflow as shown in figure 3.8.

3.6.1 Pre-Processing and Data Transmission

As an optional data transfer station, when new datasets come from remote PACS system, the server will do off-line pre-processing on demand to:

- **Build index files:** It keeps a dataset-index file to track the latest dataset and volume-index

files to maintain the pre-processed information for each volume.

- **Generate quality metrics:** It quantifies the quality of the original DICOM images from the CT or MRI scanners and helps filter out low quality datasets. When users request to browse the available datasets, those quality metrics would help to selected the desired ones.
- **Generate organ masks and center lines**

3.6.2 Share Views Across Platforms

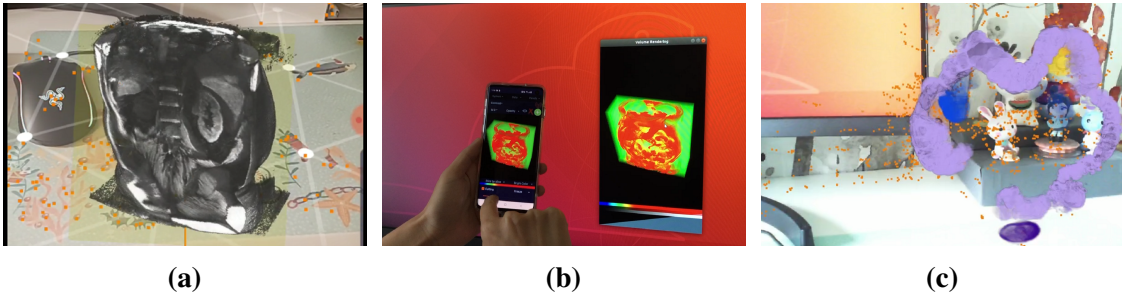


Figure 3.9. Share view between Android phone and desktop: (a) View in AR context on a smartphone, (b) Share view in non-AR context, and (c) Share view in AR context.

Users can share views with other users on different platforms via the server (Fig. 3.9). To initiate this, one user’s Android phone becomes the ”host client” and controls the view; then other clients, either with mobile devices or desktop computers, connect to the server to get their views synchronized to the ”host client”. This functionality also works on AR devices, however, compared to the non-AR cases which share the whole view with others, it doesn’t share the camera view but only the 3D dataset manipulations. This is because, in an AR environment, we want to give each user their own perspective on the dataset, so that a doctor can discuss a dataset with a patient.

3.7 Results

Our system provides two volume rendering methods to view the same datasets.

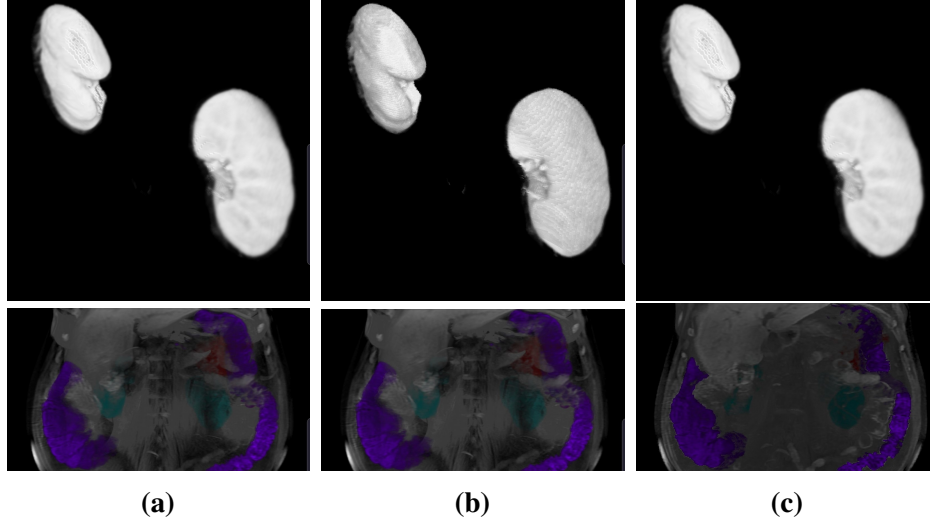


Figure 3.10. Compare rendering with (a) texture-based method, (b) ray-casting method, and (c) ray-casting with the adaptive sampling method.

Table 3.1. Compare FPS among rendering methods

	Volume	Masked Volume	Masked Mesh	Masked Volume+Mesh
Texture-based	59.9	59.8	59.8	48.5
Raycasting	59.8	34.2	59.8	26.1
Raycasting(adp)	59.8	33.4	59.8	23.8

Qualitative results: The texture-based method is fast for moderately sized datasets, and surface-based and volumetric representations can easily be combined. It works better when multiple opacity widgets are applied together. However, there are artifacts when a stack is viewed from close to 45 degrees (Fig. 3.5a). In comparison, the ray-casting method provides more details. Fig. 3.10 compares views rendered with texture-based, ray-casting, and ray-casting with adaptive sampling step methods. In most cases, adaptive sampling methods take more sample steps in a denser area, which enhances the details. However, if the selected area is non-convex, the ray-casting method eliminates the details inside the concave regions. With adaptive sampling steps, this elimination can get worse.

Quantitative results: In real practice, users may use different combinations of rendering parameters for different visualization tasks, which highly affects the performance. We use an

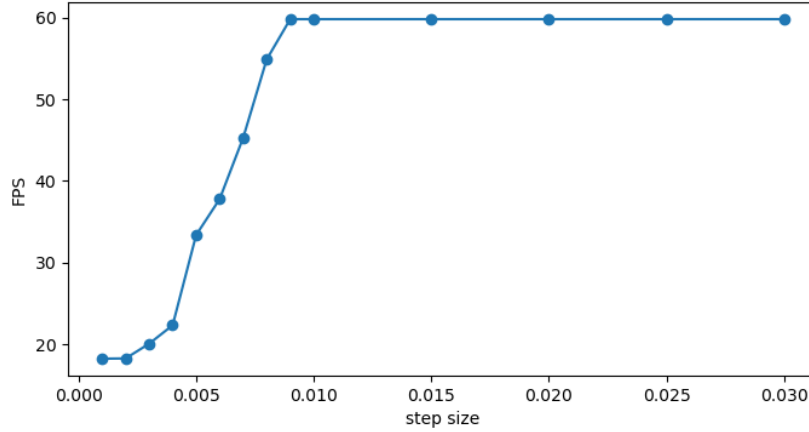


Figure 3.11. Rendering performance of adaptive raycasting method with different sampling step sizes

MRI volume dataset of size $(512 \times 512 \times 144)$ and set up this application in default contrast (0, 1, 1) and opacity (1, 1, 2, 2, 1) settings. Fig. 3.11 compares the frames per second(FPS) of our adaptive raycasting method with different sampling step sizes. We observed that if the step size exceeds 0.025, there will be discernible artifacts on the volume.

Table 3.1 compares FPS of the application with different rendering methods. For this comparison, we set the sampling step of raycasting rendering to 0.05. From the table, we see that all the rendering methods could render the whole volume in nearly 60FPS. To render a region that contains more details, for example, when we render the masked volume which only shows the organs, the ray-casting method is much slower. For this dataset, the maximum number of triangles to render the organ mesh is $512 \times 512 \times 144 \times 5 = 188743680$ and the application is able to seamlessly render the meshes while maintaining a near 60FPS.

3.8 Conclusion

In this project, we created a server-aided DICOM viewer for Android mobile devices. Our results show that we can do real-time volume rendering with both texture-based and ray-casting methods to show 3D volumetric DICOM datasets. Users have flexibility to adjust the rendering

parameters, cut into the volume, separate out major organs, and save or load those settings to or from a file. By connecting to our server, a user can also share the viewing parameters with others in real-time. Future research should be devoted to the development of a better user interaction experience in augmented reality (AR) scenarios adapted to different AR devices with support for multi-user cooperation. Some of the functionalities of our server can still be optimized, such as providing segmentation results on the fly with the request for specific parts of the tissue.

3.9 Acknowledgments

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Chapter 3, is largely a reprint of the material as it appears in Zhang, Menghe and Jürgen P. Schulze. “Server-Aided 3D DICOM Image Stack Viewer for Android Devices.” *Electronic Imaging, The Engineering Reality of Virtual Reality* (2021). The dissertation author was the primary investigator and author of this paper.

Chapter 4

A DirectX-Based DICOM Viewer for Multi-User Surgical Planning in Augmented Reality

4.1 Abstract

Preoperative medical imaging is an essential part of surgical planning. The data from medical imaging devices, such as CT and MRI scanners, consist of stacks of 2D images in DICOM format. Conversely, advances in 3D data visualization provide further information by assembling cross-sections into 3D volumetric datasets. As Microsoft unveiled the HoloLens 2 (HL2), which is considered one of the best Mixed Reality (XR) headsets in the market, it promised to enhance visualization in 3D by providing an immersive experience to users. This chapter introduces a prototype holographic XR DICOM Viewer for the 3D visualization of DICOM image sets on HL2 for surgical planning. We first developed a standalone graphical C++ engine using the native DirectX11 API and HLSL shaders. Based on that, the prototype further applies the OpenXR API for potential deployment on a wide range of devices from vendors across the XR spectrum. With native access to the device, our prototype unravels the limitation of hardware capabilities on HL2 for 3D volume rendering and interaction. Moreover, smartphones can act as input devices to provide another user interaction method by connecting to our server. In this chapter, we present a holographic DICOM viewer for the HoloLens 2 and contribute (i)

a prototype that renders the DICOM image stacks in real-time on HL2, (ii) three types of user interactions in XR, and (iii) a preliminary qualitative evaluation of our prototype.

4.2 Introduction

Surgical planning with medical imaging in a DICOM format is a demanding process. Traditionally, viewing and planning on 2D screens make it challenging for clinical practitioners to extract 3D information such as anatomical structures, the regions of interest, and spatial relationships among the image set.

3D volumetric visualization in Mobile Augmented Reality (MAR) solves this problem by integrating the volumetric object with the physical environment for mobile devices. Our previous work on Android (186) developed an application to load, view, and interact with 3D medical volumes in traditional 2D screen and AR scenarios.

To further allow hands-free operations, we adapt it to HoloLens 2 with our graphical C++ MR rendering engine using the native DirectX11 API and HLSL shaders to boost the device's performance. We also show three user interaction methodologies for different tasks: 1) we design our own interaction set (3D interactions) and interfaces (virtual 2D plane touch) for unique user interactions using OpenXR APIs; 2) with matched functionalities to our Android DICOM Viewer, we make Android phones as input devices to MR applications. Fig. 4.1 shows the categorized feature list. We will detail the implementation of the extended features in this section.

4.3 Related Work

4.3.1 Holographic DICOM Viewer Prototypes

Mojica et al. (114) proposed an AR DICOM Viewer prototype for the first generation of the HoloLens. To accelerate volume rendering, they only render the plane under a specific setting to avoid rendering the whole data volume. Remote rendering is another solution. Frohlich

Category	Function	Details	GLES-based	D3D-based
Load Data	From the local machine			
	From server			
Save Setting	Local machine			
Volume Rendering	Texture-based			
	View-aligned			
	Raycasting			
Transfer Function	Contrast Enhancement	Range and brightness		
		CLAHE		
		Addition value		
	Opacity Widgets	Add, remove, and change visibility		
		Graph visualization		
	Color Transfer Schemes	Grayscale		
		HSV(hsv, 0-255)		
		BrightColor(hsv, 0-180)		
		Fire		
		CET-L08		
Cutting Plane				
Mask	Organ Mask	Organ Volume		
		Organ Mesh		
	Centerline	View centerline		
		Cutting plane through centerline		
Video Recording				

 Functionalities in previous work
  Matched features
  Extend features

Figure 4.1. List of the functionalities on GLES-based and D3D-based applications.

et al. (48) proposed it as part of a dedicated workstation with a wireless connection that enables real-time computation on MR headsets. Their latest work (116) is deployed in a two-CPU fashion: parts run on the HoloLens and parts run on an external PC connected through Wi-Fi to enable real-time experience.

HoloDICOM (63) is a standard DICOM image stack visualization tool targets at the HoloLens 2. It contains tools for volume manipulation, a 2D slicer, and an intuitive floating 2D user interface. However, only one instructor can interact with the application, while others could only observe the interfaces.

4.3.2 Interaction with 3D Objects

3D selection in mid-air is commonly used in XR applications. However, interacting with faraway objects and dense object selection still create problems in terms of user fatigue (70). We have been exploring to apply 2D touch to achieve 3D selection in AR (183)(184)

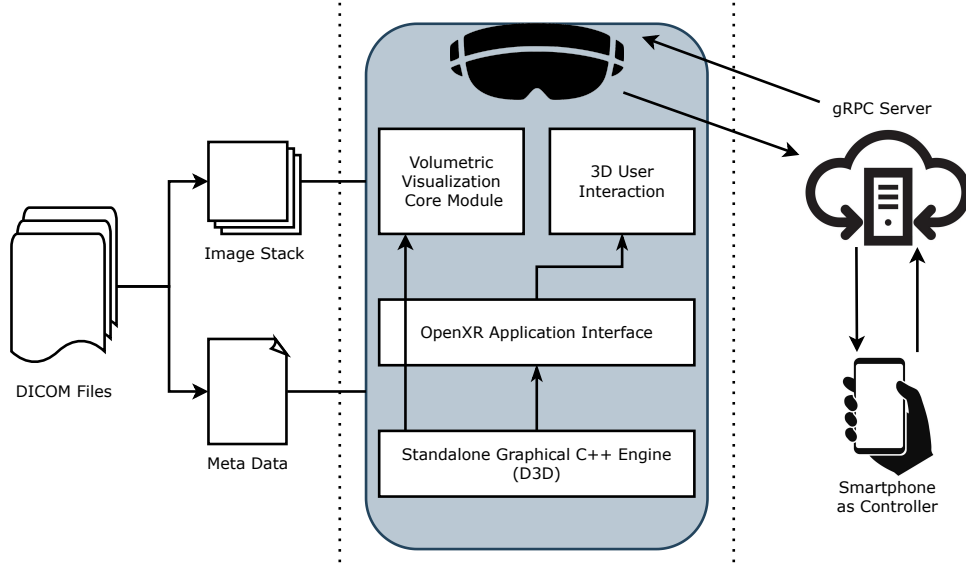


Figure 4.2. System structure: Offline DICOM data preprocessing and anonymization (left), Direct3D-based DICOM viewer prototype structure (middle), and smartphone as input device (right).

The idea of tuning smartphones into input devices for HMDs attracted the designers' interest in various interactions. Karan et al. (78) enhanced the AR game experience by creating new interaction methods through a smartphone used as a game controller. Their remote input SDK makes connections between Unity applications developed for XR devices. Buschel et al. (22) contributes an exploration of smartphone-based interaction techniques for 3D pan and zoom, which are two essential tasks in HMD applications. They designed five 2D touch screen gestures mapped to pan & zoom operations in 3D. MARVIS (91) combines smartphones and HMD AR for data analysis.

Until now, few medical imaging-based surgical planning solutions on the HoloLens take full advantage of the flexibilities of the native engine.

4.4 System Design Overview

Fig. 4.2 shows our system's components integrating an offline DICOM data preprocessor, a Direct3D-based DICOM Viewer, and the setup for smartphones as user input. Our previ-

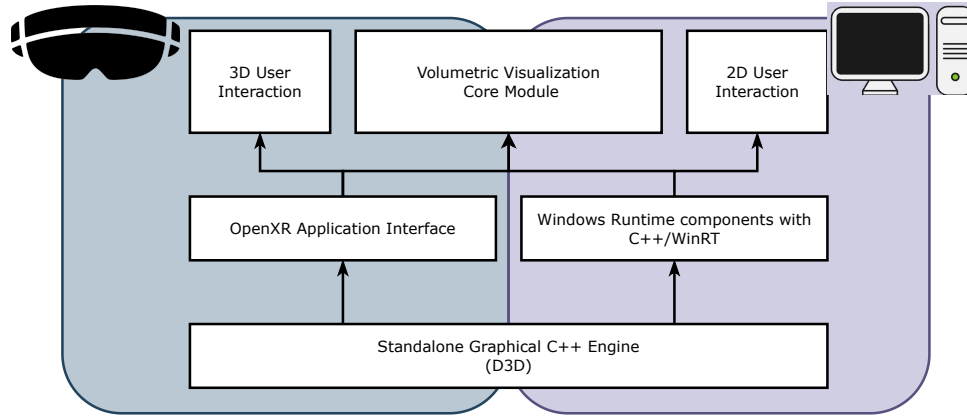


Figure 4.3. Direct3D based DICOM viewer on HoloLens 2 and desktop.

ous work (186) introduces the DICOM data preprocessing tool on a desktop that categorizes information and anonymizes sensitive data. Then the graphical engine based on UWP with DirectX 11 API allows developers to manage hardware resources efficiently. The 3D renderer with OpenXR enables potential deployment on a wide range of MR devices. On the project structure side, as HL2 moved to a 64-bit Windows 10 machine that runs UWP applications, our prototype branches into two applications: one for HL2, the other running on a Windows 10 desktop. Fig. 4.3 illustrates the relationship between the two applications.

4.5 Direct3D-based DICOM Viewer Implementation

4.5.1 Smartphones as User Input Devices

One of the advantages of setting up the gRPC server in a local area network is that either HL2 users or other users can more flexibly input and control the AR application. As described in previous work (186), such a server is implemented with a gRPC framework that can run in any environment. We designed the functionalities on this D3D based DICOM Viewer to match those on a smartphone, following previous work (186), which allowed all operations on the smartphone to be translated and passed to the gRPC server seamlessly.

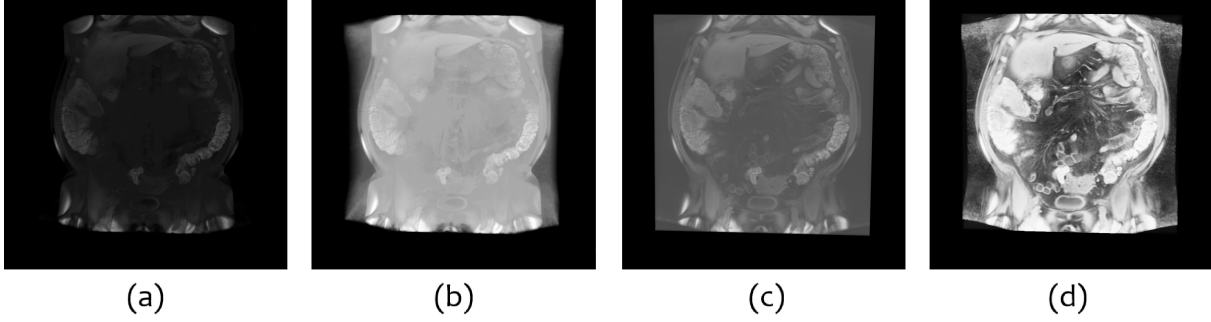


Figure 4.4. Comparison of different contrast enhancement methods: (a) raw data volume, (b) only increasing the brightness, (c) only increasing the base value, and (d) using CLAHE.

4.5.2 Functionalities

Contrast Enhancement

Previous work (186) describes a uniform enhancement of contrast and brightness. An extension of the contrast enhancement came from the fact that our DICOM data has a resolution of 12 bits per pixel. The strategy of compressing the original 12 bits for a typical 8-bit display reduces the image contrast. Normally, we would discard the last four digits to map the data to 8 bits or use some linear mapping, but neither solves the problem of displaying these high dynamic range images on regular displays.

Therefore, we chose to integrate Lucknavalai and Schulze’s work (103) to perform real-time 3D Contrast Limited Adaptive Histogram Equalization (CLAHE) to enhance 3D medical image stacks. Fig. 4.4 compares the same volume data under the same setting only applies different contrast enhancement methods. Notice that for comparison, we only change one factor for each view. However, combined adjustments can be used to improve the quality further.

Video Recording

We implemented a spectator view mode, which only renders the front RGB camera for live preview on the HoloLens 2. The initial motivation is that when recording for a demonstration video or streaming, the frame rate on the HoloLens 2 would decrease as it does the volumetric rendering for three different views per cycle. Due to the heavy computational intensity and limited

pixel fill rate, the resulting low frame rate is not acceptable for interactive usage. Therefore, our solution only renders one view from the RGB camera and doubles the frame rate compared with regular use.

HL2 provides a “Render from the PV camera” option on the Windows Device Portal. However, instead of handling all reprojection calculations and rendering the third view automatically, this option toggles a flag on the Hololens. It makes data coming from the PV camera available programmatically. We still need to enable corresponding OpenXR configs and manually handle the additional reprojected rendering for the PV camera. The data from the PV camera is self-contained enough to perform complete volumetric rendering individually without the need to do any computation from the regular display rendering. The rendered virtual hologram will then be blended with the RGB video captured by the PV camera to produce the final spectator view.

4.5.3 Marker-based 3D Object Placement

To achieve a marker-based 3D object placement and put multiple users under the same reference frame, we combine the marker tracking and the Hololens tracking. We integrate ArUco marker tracking (118) with OpenCV (126) on the Hololens. Due to performance concerns, we implement the OpenCV thread parallel to the main rendering thread. The OpenCV builds the reference frame and tracks the printed ArUco marker based on the images from the Left-Front VLC camera every few rendering frames. Then we create/adjust a spatial anchor onto the detected ArUco marker and use it as the frame of the reference across all devices.

OpenXR defines XrSpace to allow applications to track real-world objects. In our Hololens application, we create the following XrSpaces:

1. Reference space: defines the original pose of the device.
2. Hand pose space: defines in the hand tracking space locally for hand interaction

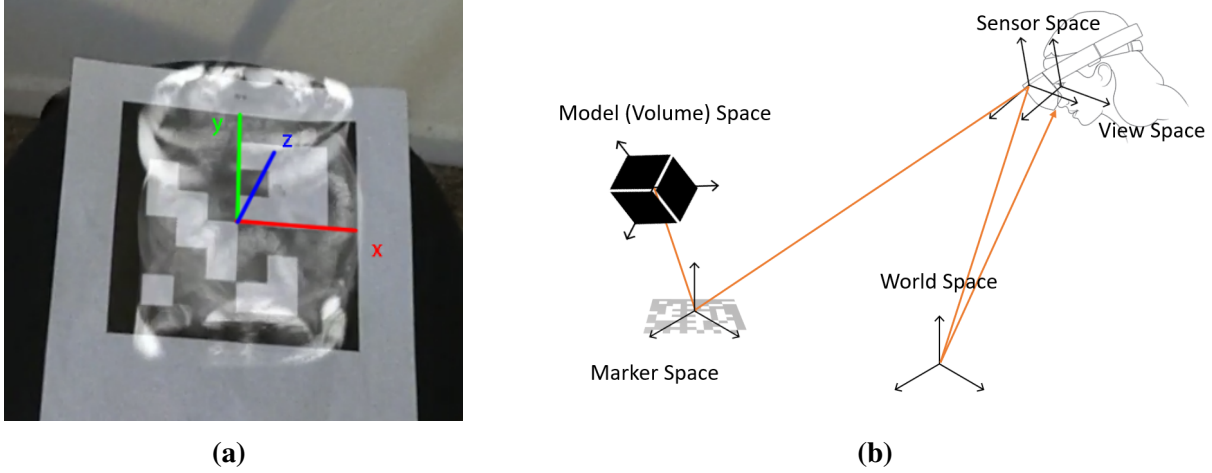


Figure 4.5. Marker-based tracking: (a) Volume positioning with the ArUco Marker in HoloLens and (b) The transformation map from volume space to view space with marker tracking.

3. Sensor space: a space provided by Research Mode (163) device sensor for coordinate alignments.

Most of the spaces can be directly updated by querying OpenXR methods, except for sensor space, which is from Research Mode in the WinRT context. We utilize the sensor's rig node GUID with the Windows Perception APIs to acquire corresponding space representation in the OpenXR coordinate system.

Given the volume model matrix *ModelMatrix*, the world to view matrix *ViewMatrix* and the projection matrix *ProjMatrix* provided by the OpenXR Swapchain configuration, a volume is rendered by $ProjMatrix * ViewMatrix * ModelMatrix$ when it is not positioned by a ArUco marker. In this case, mid-air hand gestures control the volume's poses (scale, translation, and orientation). The hand movements in the *HandSpace* are first converted into *WorldSpace*, then multiplied by sensitivity value for finer control of the volume pose, and finally directly applied onto the *ModelMatrix*.

We handle the case where we use the detected ArUco marker to position the volume differently. OpenCV detects the printed ArUco markers in the sensor's image and returns the marker's transform *Marker2Sensor* with respect to the LF VLC camera. The sensor space repre-

Category	Function	Details	Interaction Method
Volume Rendering	Switch volume rendering methods and tune parameters		
Transfer Function	Contrast Enhancement		
	Opacity Widgets		
	Color Transfer Schemes		
Manipulation	Volume Manipulation	Translation	
		Rotation	
		Scaling	
	Annotation		
Menu	Show/Hide Menu		
	Menu Selection		
Cutting Plane	Control the cutting direction and depth		
Mask	Organ Mask	Organ Volume	
		Organ Mesh	
	Centerline	View centerline	
		Cutting plane through centerline	

Smartphone Control

3D User Input

2D Plane Touch

Figure 4.6. User interaction tasks with corresponding method.

sensation in OpenXR provides us up-to-date sensor transform $Sensor2World$ in the $WorldSpace$. With this information, we can acquire the marker transform in the HoloLens $WorldSpace$ by $Marker2World = Sensor2World * Marker2Sensor$. The volume is then rendered with the matrix transformation $ProjMatrix * ViewMatrix * Marker2World * ModelMatrix$ as shown in Fig. 4.5. In this case, we make the detected marker the reference frame's new origin. All 3D interactions are performed locally as to this new reference frame and synchronized across different clients. By default, we render the volume on the marker when there is no 3D interaction (Fig. 4.5).

4.6 User Interactions

This section presents three types of user interaction methods under different tasks in the AR application. Fig. 4.6 categorizes the interaction tasks and assigns the most intuitive interaction method to them.



Figure 4.7. Virtual-force sketch for 2D data annotation: (a) screenshot of 2D sketching and (b) side-by-side illustration of the volume and annotation data.

4.6.1 Virtual 2D Plane Touch

We first created an xrHand system to achieve direct touch on a virtual 2D plane instead of pinch gesture as the "select" operation. The xrHand system actively tracks the right/left-hand index tip. We draw a small sphere around the tip and check the distance between the sphere to the target plane.

When drawing on a modern digital tablet, an intuitive stroke changes the brush size adaptively according to the pressure on the touch screen. The function that transforms the pressure into brush size is called pressure sensitivity. However, as the mid-air interaction doesn't have physical planes to provide actual pressure, we need to construct a virtual pressure mapping to gain pressure sensitivity. Our method is inspired by VirtualForce (190), which proposed calculating the sketching force based on the difference between the user's physical hand position and their hand avatar in the Virtual Reality (VR) environment.

We transformed this concept into AR. As the index finger plunges into the virtual canvas, the hand-unaligned distance (d) determines the pen pressure on the canvas. The deeper the finger goes, the more pressure will be on the canvas (Equ.4.1). Then with a linear pressure sensitivity function, we map the virtual pressure to the sketch stroke size for planar data annotation (Fig. 4.7).

$$d = planeNormal \cdot (P_r - planePoint), P_v = P_r - d * planeNormal \quad (4.1)$$

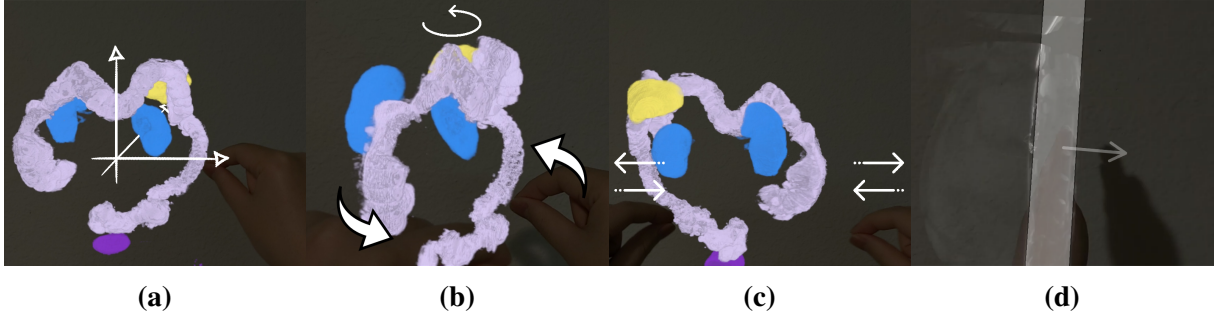


Figure 4.8. Four different free-hand 3D interactions: (a) translation, (b) rotation, (c) scaling, and (d) cutting plane.

4.6.2 3D User Interaction

We provide single-hand and two-hand gesture control for basic volume interactions and a cutting plane with 6 degrees of freedom. The user can manipulate the translation of the volume by firstly grabbing and then moving the single hand around as shown in Fig. 4.8a. With two hand gestures, the user can firstly hold the volume with both hands and then control the orientation and scale of the volume. Fig. 4.8b shows that grabbing and rotating two hands relatively will apply the same amount of rotation onto the volume. As shown in Fig. 4.8c, moving two hands away from each other enlarges the volume. Conversely, moving two hands closer will shrink the volume. In the Fig. 4.8d we use the palm poses to control the cutting plane directions and depth.

4.7 Experiments

We measured the frame rate while moving the volume on five scripted paths: rotating the volume around its y-axis and its x-axis, respectively, while being either 2m or 1m away from the user. Each of the rotations took 10 seconds. Furthermore, we moved the volume along the z-axis, starting again at a 2m to 1m distance. This movement path required 10 seconds to complete. All frame rates were measured by averaging over 500 ms periods. The experiment volume contained 144 scans, each of 512×512 pixels. The measurements are on three rendering methods with parameters as shown in Fig. 4.9.

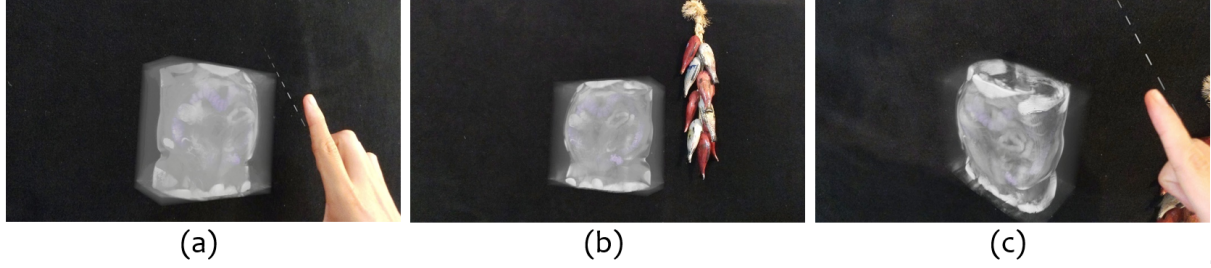


Figure 4.9. Screenshots of a volumetric data rendered with: (a) texture-based method, (b) view-aligned slicing method, and (c) raycasting method.

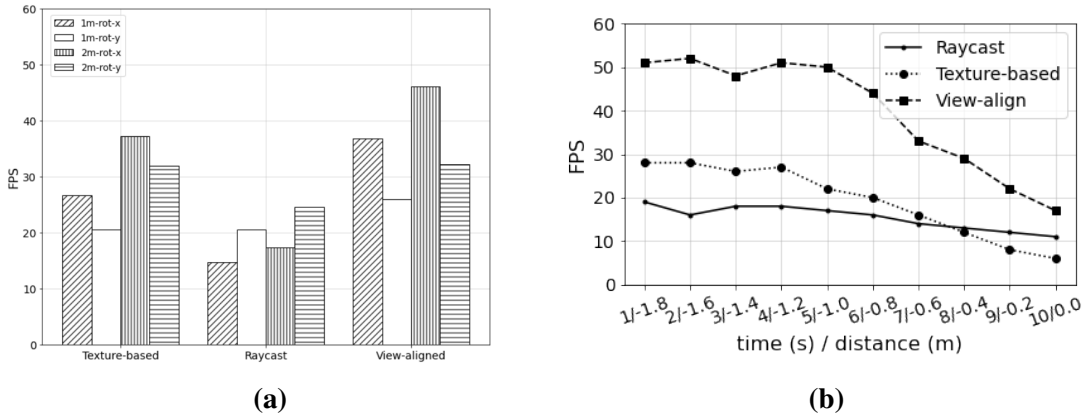


Figure 4.10. Experiment results: Average frame rates during (a) a full rotation around the x-axis and y-axis setting at 1m and 2m distance, and (b) a uniform rectilinear motion from 2m to 0m.

In Fig. 4.10a, we show the frame rates for the rotation around the x-axis and y-axis at 1m and 2m. View-aligned rendering methods reach the highest frame rate at 46 fps rotating around the x-axis at a 2m distance. This method performs the best overall for reducing the number of slices that need blending to get a decent view yet fewer artifacts—followed by the texture-based rendering method, which manages to exceed 30 fps rotating at a 2m distance. The raycasting method is overall costly, although it accumulates its values adaptively. It performs better for a comparably static view scenario.

Fig. 4.10b shows the frame rates for uniform rectilinear motion from 2m to 0m away. The plot shows the frame rate change across the 2m movement in 10 seconds. For the View-aligned and Texture-based methods, from the beginning 2m to 1m, the frame rate drops slowly while it

drops faster from 1m to 0m. As the volume moves closer, it fills the entire two views, making the alpha-blending much slower for reading from and writing to back buffer. The change of the Raycasting method is minor because instead of alpha-blending, it works within a compute shader to sample along a ray within limited steps.

4.8 Conclusions

In this chapter, we presented a prototypical Mixed Reality DICOM viewer based on a DirectX-based native engine. The functionalities of this prototype match a previously developed DICOM Viewer-Android system, while optimizing for two-views head-mount displays. The matched functionalities make it possible and intuitive to remote control the view inside a HoloLens with a connected smartphone. It also enables new possibilities, such as supporting collaborative work across platforms. Our testing results shows that it is difficult to achieve 60 fps rendering on two views simultaneously while maintaining a high-quality rendering for a volume. However, by switching among different rendering methods while adjusting the parameters, one can find the best balance between frame rate and quality.

4.9 Acknowledgments

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Chapter 4, is largely a reprint of the material as it appears in Zhang, Menghe, Weichen Liu, Nadir Weibel, and Jürgen P. Schulze. “A DirectX-Based DICOM Viewer for Multi-user Surgical Planning in Augmented Reality.” In *Advances in Visual Computing: 17th International Symposium, ISVC 2022, San Diego, CA, USA, October 3–5, 2022, Proceedings, Part II*, pp. 217-228. Cham: Springer Nature Switzerland, 2022. The dissertation author was the primary investigator and author of this paper.

Chapter 5

E-FaceAtlasAR: Extend Atlas of Facial Acupuncture Points with Auricular Maps in Augmented Reality for Self-Acupressure

5.1 Abstract

Acupuncture is a form of alternative medicine from ancient times and adapted to modern medicine. One typical practice of acupuncture is putting pressure on specific sites (acupuncture points, or acupoints) in the body, called acupressure. Self-acupressure refers to people applying pressure on acupoints using fingers, palms, or special devices to themselves. It has been widely applied because of its convenience and effectiveness. However, localizing the acupoints in any acupuncture practice requires expert knowledge. Novices without any medical background typically find it difficult because of the lack of visual cues. In this project, we present E-FaceAtlasAR, a prototype system that localizes and visualizes facial acupoints and auricular zone maps in an augmented reality (AR) context. The system first localizes facial acupoints and auricular zone maps in an anatomical yet feasible way. Then, it overlays the requested acupoints and auricular zone maps on the ears in AR. We adopt Mediapipe, a cross-platform machine learning framework, to build the real-time pipeline that runs on desktop and Android phones. Also, we conducted extensive experiments to show its effectiveness and robustness. With this system, users, even not professionals, can position the acupoints quickly for their

self-acupressure treatments.

5.2 Introduction

Acupuncture (77) is a key component of traditional Chinese medicine (TCM). Based on the symptoms, acupuncturists stimulate specific anatomic sites commonly by needling, massaging, or heat therapy. Those anatomic sites, called acupuncture points (or acupoints), lie on different meridians, where the life energy (called “qi”) flows. Scientific studies have confirmed the effectiveness of acupuncture for many conditions (19) (181) (170). Acupuncture practice relies on experienced acupuncturists to localize the acupoints from body acupuncture maps, which requires long-term theory study and clinical practice. Patients could do needleless self-acupuncture treatments like acupressure safely and conveniently. However, novices without any medical background typically find it challenging because of the lack of visual cues. They usually have difficulty localizing the target acupoints on themselves based on standard descriptions, pictures, and models.

Recently, Augmented Reality (AR) (16) is considered a remarkable method to solve this problem. By projecting the acupoints onto the skin, AR applications provide users with more intuitive guidance. For facial acupuncture, H. Jiang et al. (73) proposed the first acupuncture training application, Acu Glass, on a head-mount display device (HMD) based on Google Glass. They generated the frontal face acupoints based on the height and the width of the input face, plus the distance between the eyes. Thus, the face landmarks for reference are too limited to adapt to different people and different poses. Another widely accepted solution is fitting a 3D Morphable Face Model (3DMM) (66) to a 2D image, like Chen et al. (29) (90). They combine facial landmarks and image deformation to estimate acupoints. However, acupoints are defined relative to anatomical landmarks according to the standards, while the deformation of 3DMM modifies the relativeness. Thus manual annotations on a standard 3D model may not correctly fit all kinds of faces (79).

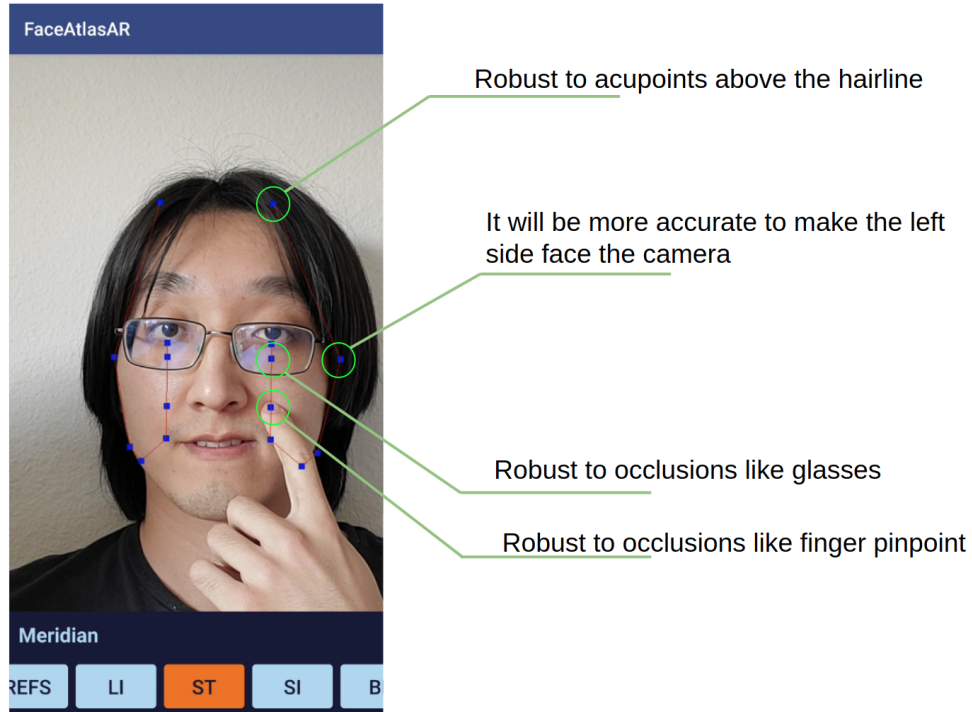


Figure 5.1. A user presses an acupoint on ST meridian channel.

Besides facial acupuncture, ear acupuncture, also known as auricular acupuncture, has also been applied for a long time. Nowadays, ear acupuncture is applied for the instant relief of pain (125), weight control (179), reduction of depression (176), and hypertension. Our application incorporates ear acupuncture guidance by overlaying the auricular zone maps on users' ears in AR. As far as we researched, there has been no report about visualizing auricular zone maps in real time.

Based on our prototype, FaceAtlasAR (185) (Fig.5.1), we present E-FaceAtlasAR, which localizes and visualizes facial acupoints and auricular zone maps in the AR context in real-time. Experiments were conducted to show its effectiveness and robustness.

In Section 5.3, we will first introduce some background of facial and ear acupuncture treatments and describe the components of an AR-assisted acupuncture solution. As for the methods and implementation, we adopt a Google open-source machine learning framework Mediapipe (104) to build the cross-platform pipeline. Within the pipeline, functionalities are

structured as standalone modules for graph organizations. Section 5.4 overviews the graph structure and divides the system into majorly two modules: facial acupoints localization and auricular zone mapping. The following two sections (Sec. 5.5 and 5.6) will illustrates the details respectively.

Compared to other AR acupoints localization systems, our work develops an innovative solution because:

- It localizes facial acupoints with consistency to the standards, which stresses the deformation issue of the 3DMM method.
- We creatively designed a scheme to transform the natural language descriptions into mathematical logic expressions (Sec. 5.5.3).
- To our best knowledge, it is the first AR acupoint localization application assisting both face and ear acupuncture (Sec. 5.6).

5.3 Background

5.3.1 Facial and Ear Acupuncture

The selection of facial acupoints is based on Chinese National Standard (CNS) *Nomenclature and Location of Acupuncture Points* (GB/T 12346-2006) and WHO *Standard Acupuncture Point Locations in the Western Pacific Region*. Fig. 5.2 visualises facial acupoints categorized by meridians.

Ear acupuncture (auricular therapy) emphasizes neurophysiologic connections between auricular reflex points and the central nervous system. It is based on the theory that every part of the body has an auricular correspondence. In 1957, Dr. Paul Nogier (122) proposed the concept of an inverted fetus map on the external ear (Fig. 5.3a), which spread to China and renewed interest in TCM (51). Later Oleson et al. (124) experimentally evaluated the claims of French and Chinese ear acupuncture. He then proposed a somatotopic mapping of the body in the external ear.

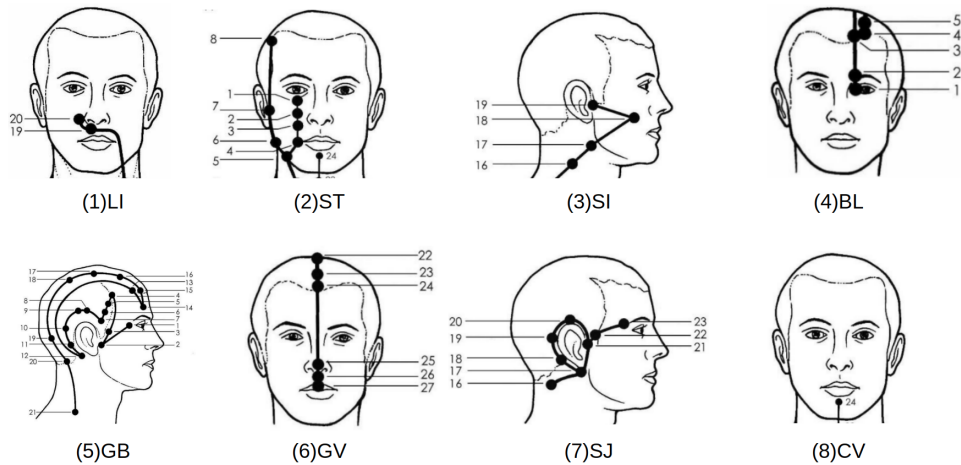


Figure 5.2. Facial acupoints grouped by meridians (7). (1) Large Intestine Channel (LI), (2) Stomach Channel (ST), (3) Small Intestine Channel (SI), (4) Bladder Channel (BL), (5) Gall Bladder Channel (GB), (6) The Governor Vessel Channel (GV), (7) Sanjiao Channel (SJ), and (8) Conception Vessel Channel (CV).

Based upon the recommendations of the 1990 WHO auricular nomenclature committee, Fig. 5.3b presents auricular zone system from CNS Nomenclature and location of auricular points (GB/T 13734-2008) (155) while Fig. 5.3c shows the revised UCLA nomenclature system.

5.3.2 AR-Assisted Acupuncture Solutions

From ancient times, standard models like the Bronze Man (175) have been commonly used for visualizing acupoint locations. Most recently, many applications show human bodies and unveil the structures near the acupoints in virtual reality (106) (76) (180). Yet, most applications lack a mechanism to practice on individuals. To achieve this, one needs to focus on: (1) a feasible yet accurate acupoint localization method, (2) a fast and robust face alignment tool, and (3) an ear anatomical landmark detection method.

Acupoints localization Back in the Bronze Man time, people created a set of theories called the Cun system to localize the acupoints either with the finger (directional or F-cun) or proportional bone(B-cun) measurements. Until now, this system is still a clinical acupoint localization method and the basis of other modern techniques. Godson and Wardle (49) screened 771 studies and summarized the modern localization methods. As the acupoints located in

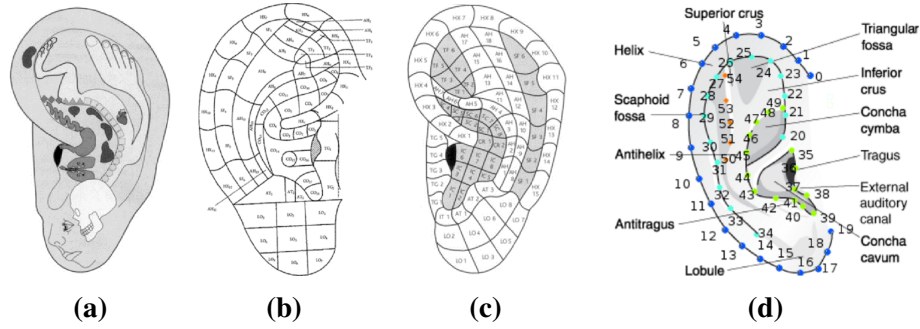


Figure 5.3. Auricular zone maps: (a) Somatotopic map originally from Nogier et al. (123), (b) Auricle zone system by CNS GB/T 13734-2008 (155), (c) Revisions of the auricular nomenclature system developed by Oleson based upon the recommendations of the 1990 WHO nomenclature committee, and (d) provided landmarks and anatomy of pinna from “In-the-wild” dataset (193).

proximity to anatomical landmarks are less variant (115), the B-cun method, as the basis of current standardized acupoints definitions, balances the accuracy and feasibility of localizing acupoints. It involves certain anatomical information and is especially suitable for comparably low-accuracy required self-acupressure treatments.

Face alignment is a computer vision technology for identifying the geometric structure of human faces in digital images. Bulat and Tzimiropoulos (21) reviewed 2D and 3D face alignment and landmark localization. Existing 2D and 3D datasets annotate a limited set of landmarks. For example, 300-W (147), the most widely-used in-the-wild dataset for 2D alignment, containing LFPW (18), HELEN (93), AFW (195), and iBUG (147), annotates only 68 landmarks per face. These points only localize some semantic regions around the eyes, eyebrows, nose, mouth, chin, and jaw, which are not dense enough for our cases. We finally adopted the work of Kartynnik et al. (79), which estimates a 3D mesh with 468 vertices in real-time. The vertices are selected manually according to expressive AR effect experiments, hence well suitable for our requirements.

Ear landmarks Recent studies make great progress working on ear images acquired from real-world unconstrained settings (42) (58) (41). Existing databases collect unconstrained

ears for recognition, including WPUTE (47), UBEAR (139), and IIT (89). These datasets are collected under a controlled environment and without annotated structures. The inner structure of the human ear is very distinctive and complex. Zhou’s “In-the-wild” ear database (193) firstly builds statistical deformable models with unconstrained ear samples. It annotates 55 ear landmarks based on the anatomical regions (Fig. 5.3d), including ascending helix (0- 3), descending helix (4-7), helix (8-13), ear lobe (14-19), ascending inner helix (20-24), descending inner helix (25-28), inner helix (29-34), tragus (35-38), canal (39), antitragus (40-42), concha (43-46), inferior crus (47-49) and superior crus (50-54).

5.4 System Overview

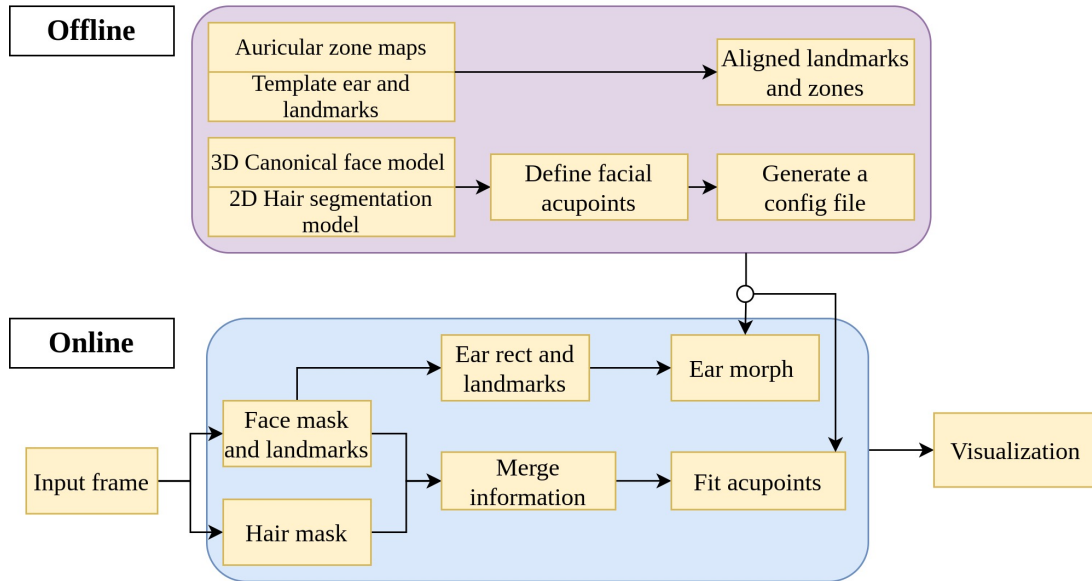


Figure 5.4. Workflow of the proposed system.

The overall procedure of the proposed system contains offline and online phases (Fig. 5.4). The offline phase prepares a facial acupoint map and two auricular zone maps. Each map describes facial acupoints (or auricular zones) relative to facial (or ear) anatomical landmarks.

The online phase includes real-time facial landmarks detection, hair segmentation, ear

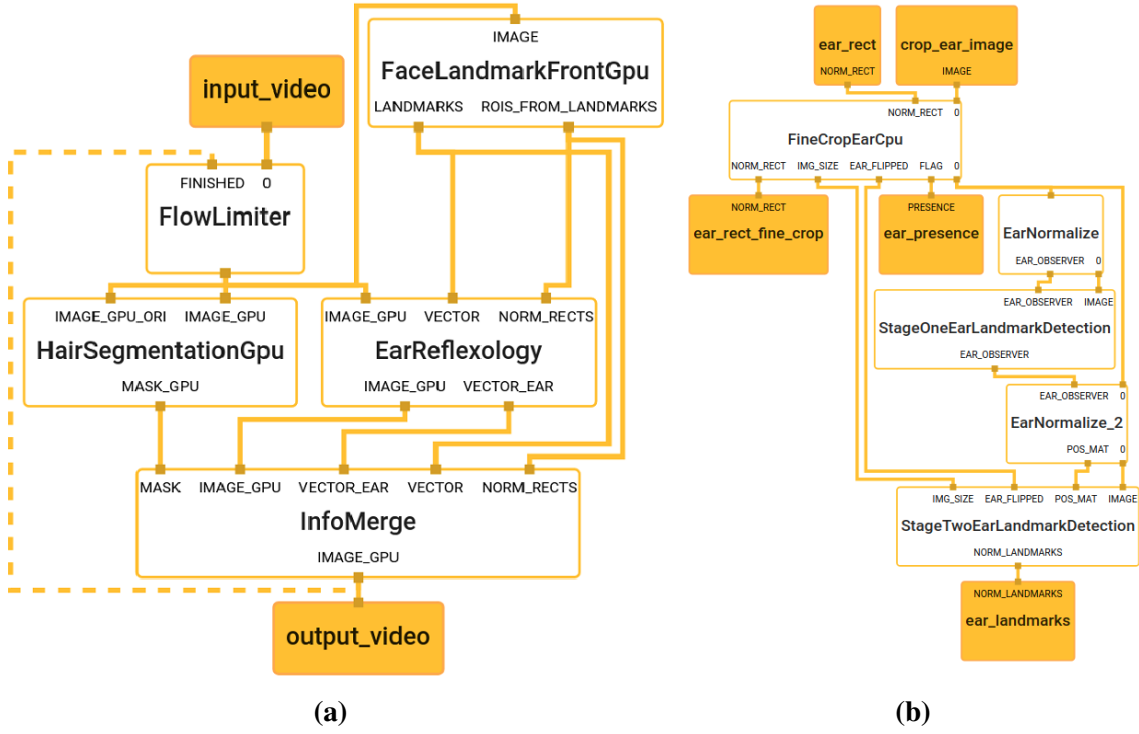


Figure 5.5. Mediapipe graphs: (a) Main pipeline graph, (b) Single ear landmarks detection graph.

segmentation, and ear landmarks localization. The prepared maps are fused into this pipeline to draw acupoints and zones. The pipeline is implemented with Mediapipe, describing the perception pipeline as a graph of modular components. We show the main graph in Fig. 5.5a. The smallest component is a Calculator, solving an individual task like model inference, data transformation, or annotation. Reusable calculators are grouped into graphs or sub-graphs, taking charge of certain tasks. The main graph is composed of multiple subgraphs and calculators. To begin with, a FlowLimiter guards the whole pipeline process and keeps track of the timestamps. Then, the pipeline connects three major subgraphs: FaceLandmarks and HairSegmentation subgraphs are for the Facial Acupoints Localization module (Sec. 5.5), while EarReflexology for Auricular Zone Visualization module (Sec. 5.6).

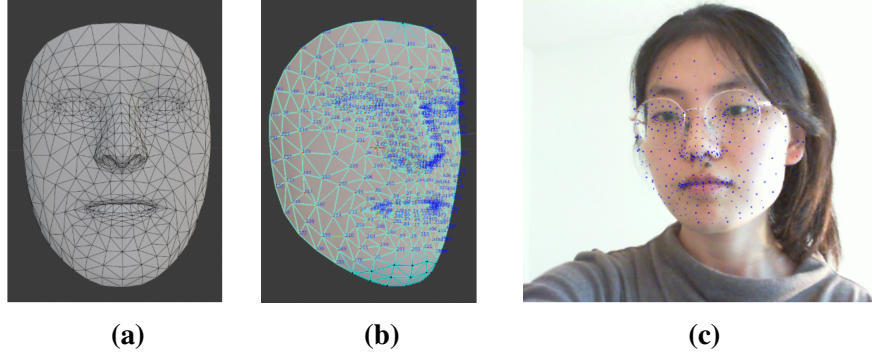


Figure 5.6. The 3D face mesh: (a) the given 3D canonical face mesh model, (b) the mesh model with its vertices and indices, and (c) the result of overlaying the 3D vertices on a user’s face.

5.5 Facial Acupoints Localization

5.5.1 Face Alignment

Given a 3D canonical face mesh model (Fig. 5.6a5.6b), we can extract a set of vertices with semantic meaning as the anatomical landmarks for further acupoints definition. To approximate the input 2D face images with such 3D mesh, we adopted a pre-trained TFLite model (79) to conduct real-time face alignment. This process majorly comprises three steps:

- **Face detection:** A lightweight face detector takes the whole frame as input to get the face bounding box and several landmarks, determining the rotation matrix of the face. This step only runs until the system finds a face to track or when the system loses track of the current face.
- **Image transformation:** The bounding box crops the frame to a face image. As the target region, the cropped image is then resized, centered, and aligned.
- **Face landmarks generation:** The pre-trained model produces a vector of 3D landmark coordinates, which subsequently gets mapped back into the original image coordinate system.

Fig. 5.6c shows the overlaying of the 468 semantic anatomical facial landmarks on a user’s face.

5.5.2 Hair Segmentation

According to the acupoints national standard, the center of the frontal hairline is a critical facial anatomical landmark. We adopt a pre-trained lightweight model (160) to compute the soft binary mask that separates hairs from the background. It embeds the result from the previous round as the alpha channel to the current RGB frame, which accelerates the process and better supports the AR scenarios. Fig. 5.7 shows the process and the hair segmentation results on a user.

5.5.3 Facial Acupoints Definition

We adapt the standard B-cun method on the head for facial acupoint localization. Generally, this method measures the length and width of each part of the body with the body surface condyles as reference landmarks and determines the position of acupoints accordingly. To represent an acupoint under the B-cun system, we need to prepare: 1) a set of semantic anatomical facial landmarks, whose details are in the Section. 5.5.1. And 2) a length between the set of two bone nodes divided into certain equal parts, called the unit Cun.

A standard unit Cun on the head is illustrated in Fig. 5.8. It identifies four reference points based on anatomical landmarks. We group them and name the group RHD:

- **RHD1, Yintang:** The midway between the medial ends of the eyebrows.

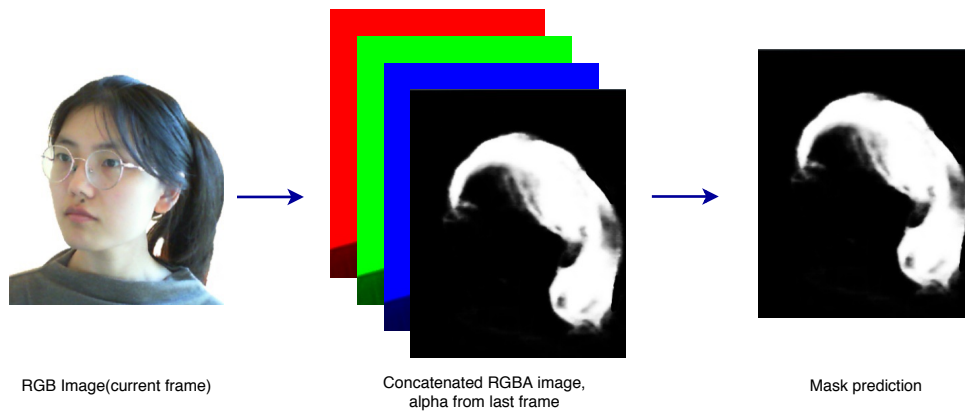


Figure 5.7. Hair segmentation workflow.

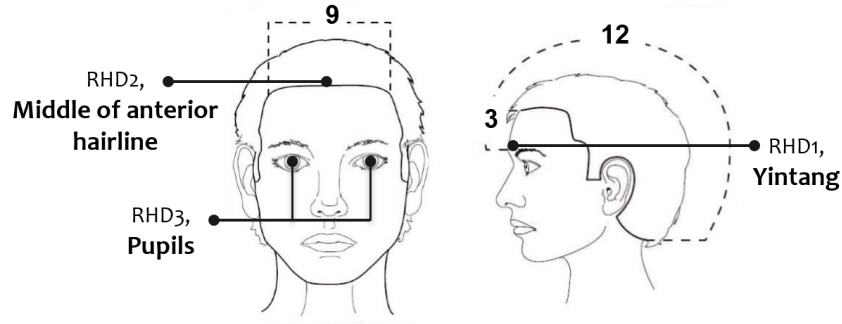


Figure 5.8. B-cun on the head from National Standard of the People’s Republic of China, Acupoints (164). Annotated the pictures from (166).

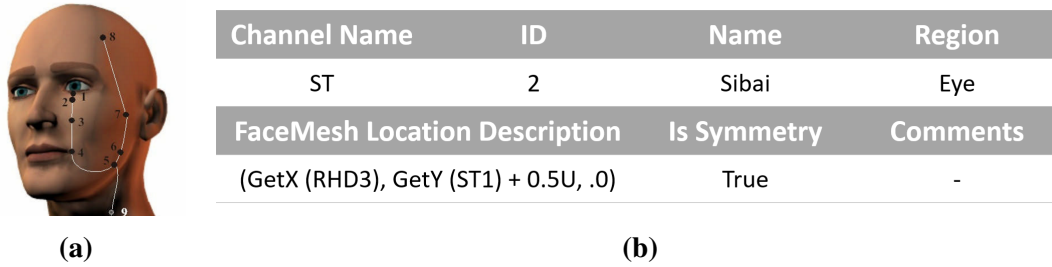


Figure 5.9. The 3D face mesh: (a) Illustration of ST channel on the head; Picture from (165), (b) Information of an example acupoint Sibai (ST2) in the data file.

- **RHD2, Middle of anterior hairline:** Intersection of anterior hairline and anterior midline.
- **RHD3, Pupils:** The left and right pupils.

From Fig. 5.8, the distance from RHD1 to RHD2 decides the unit Cun as $U = d_{RHD1 \rightarrow RHD2} / 3$. Based on the 468 semantic anatomical facial landmarks and the unit Cun, we now describe the locations of 69 facial acupoints with respect to the 3D mesh coordinates. To keep it simple in this paper, we will take acupoint ST2 as an example to illustrate this process. With the standard location “On the face, on the infraorbital foramen, 0.5 Cun inferior to ST1 when eyes focus.”, Tab. 5.9b shows the information we kept for ST2. Note that, we translate the standard location description based on the Cun system to the FaceMesh Location as a 3D coordinate relative to reference point RHD3, acupoint ST1, and the Cun measurement.

With these FaceMesh Locations, the system can automatically annotate all 69 acupoints

on the face mesh coordinate in the online phase. Finally, we group the acupoints in the same meridian channel and connect the points in order of the flow. Under this rule, the previously stated acupoint, Sibai, belongs to the ST (Foot's Yang Supreme Stomach Meridian) channel. Fig. 5.9a illustrates all acupoints on the ST channel and their flow.

5.6 Auricular Zone Mapping

We started by preparing two auricular zone maps (Fig. 5.10b5.10c) according to the standards (Fig. 5.3b5.3c) as templates. Each template is described as image I with its corresponding set of landmarks L_I (Fig. 5.10a). As the localization of these zones also rely on ear anatomical landmarks, in order to draw the zones, a common sequence of steps includes:

- Capture each frame as image J .
- Get the cropped ear image (Sec. 5.6.1) from J , each of which as J_c , and its landmarks set L_J (Sec. 5.6.2).
- Make J_c the same size as I , while transforming L_J to L_I coordinate accordingly. Then L_J and L_I become correspondence points.
- Obtain the triangle list T from L_J (Sec.5.6.3).
- Warp and alpha blend image I and image J_c to get the result M (Sec.5.6.4).
- Now, the target points on the morphed image M are correctly aligned.

5.6.1 Ear Detection from Facial landmarks

We conduct the ear detection by making a quick coarse estimation of an ear bounding box from the facial landmarks (Sec. 5.5.1). The measuring of a bounding-box position is to find the location of the superior attachment of the pinna. In photography, the term 3/4 portrait commonly refers to a shot where 3/4 of the model is visible in the frame. Practically, the model's

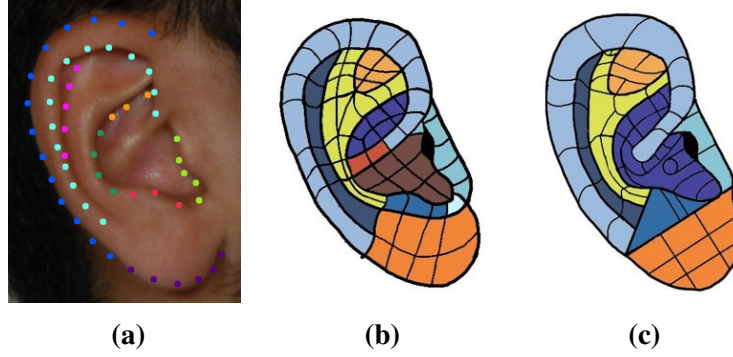


Figure 5.10. A selected image that is: (a) annotated with 55 landmarks, (b) transformed to Oleson's auricular zone maps, and (c) transformed to GBT13734 standard auricular zone maps.

head is turned away slightly, such that the ear on the opposite side of the camera is just out of the shot. Even though different face and ear shapes make the angles of heads vary, the facing angle is about 45° .

Given a side view, we first estimate the head pose from a selected set of face landmarks. The pose estimation finds a head's relative orientation and position concerning a camera, usually described as a Perspective-n-Point (PnP) problem. With a calibrated camera, N 3D object points, and the corresponding 2D projection points, it determines the pose of a target object. We apply OpenCV `solvePnP(p3d, p2d, cM, dist)` with selected 2D and 3D landmarks as input. Kartynnik et al. (79) present a canonical 3D facial mesh where they estimate 3D positions for vertices. Since $N \geq 4$, we choose six vertices accordingly and illustrate them on the provided canonical mesh (Fig. 5.11a). The points are:

- P_1 : Tip of the nose: $(.0, .0, .0)$
- P_2 : Middle point of the chin: $(.0, -381.915, 129.21)$
- P_3 : Left corner of the left eye: $(-222.293, 189.5445, 215.109)$
- P_4 : Right corner of the right eye: $(222.293, 189.5445, 215.109)$
- P_5 : Left corner of the mouth: $(-122.8105, -160.786, 159.586)$

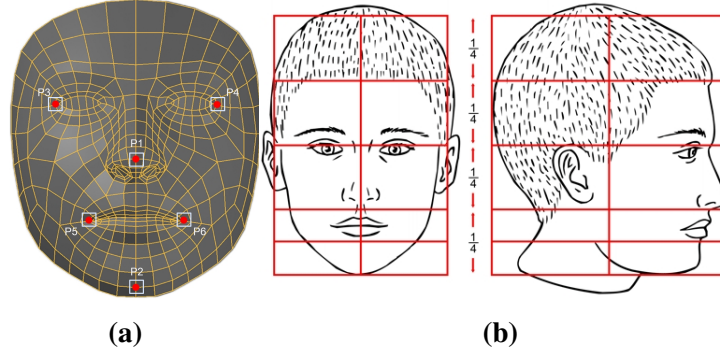


Figure 5.11. Head proportion and Mesh topology: (a) The predicted mesh topology given by (79) annotated with the selected 6 points. (b) The proportion of the head (13).

- P_6 : Right corner of the mouth: $(122.8105, -160.786, 159.586)$

Then we get a rotation vector $\vec{V}(x, y, z)$ indicating the head pose towards the camera. The rules to generate ear bounding boxes are:

- If the rotation angle on Y-axis is within 45° , both ears might be seen. Otherwise, only one ear shows up.
- Rotation on X-axis determines the vertical range. Rotation on Z-axis controls the horizontal one.

The third quarter contains most of the features when the head portrait is divided into four equal quarters vertically. As illustrated in the Fig. 5.11b, at the top of this section, the eyes are usually level with the ears, and at the bottom, the nose is roughly level with the ear lobes. We picked the middle point between the two eyes, nose tip, and two selected landmarks on the face border to determine the coarse bounding box of the ear.

Given the current captured GPU frame and the coarse potential ear rectangles inferring from face alignment, there is an optional FineCropEar module (Fig. 5.5b) before actual landmarks localization that crops the regions of interest (ROIs) much more precisely and rule out false detections. Fig. 5.12 presents the steps to obtain a more precise ROI from a coarse one. First,

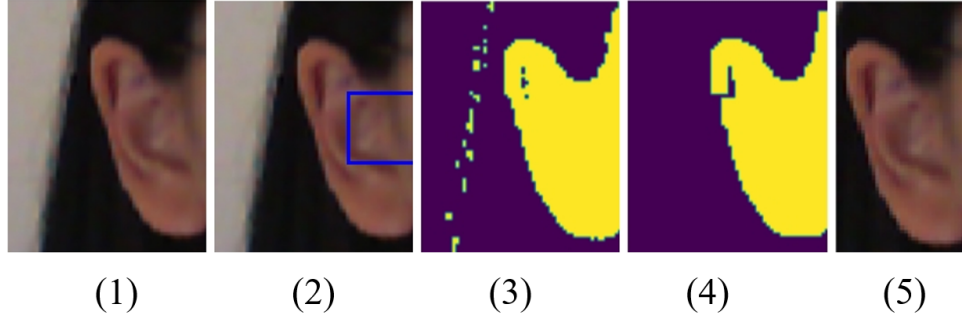


Figure 5.12. FineCropEar module process. (1) An input coarse cropped ear image, (2) The image patch to decide skin color boundaries, (3) The ear mask from skin color detection, (4) The mask after an opening operation, and (5) The final cropped ear image.

we convert the image from RGB space to the HSV color space and apply HSV color range limits to the HSV frame. The lower- and upper-bound of HSV color is from the color range in a sample patch between ear and face. The patch decides the skin HSV color boundaries, thus leveraging different lighting conditions and ethnicities. Then an opening operation removes small false-positive skin regions. The contour with the bounding rectangle is the final target ROI.

5.6.2 Ear Landmarks localization

We utilize an unconstrained ear recognition framework from Hansley et al. (58) that works on ears-in-wild scenarios. It resolves the problem of pose variation by designing a two-stage landmark detector. We modified the original framework with support to project the generated 55 landmarks back to the original image and construct the EarLandmarksSubgraph as shown in Fig. 5.5b. Fig. 5.13 gives an example of our framework based on their work. Comparing landmarks results between the first stage (Fig. 5.13 (5)) and the second stage (Fig. 5.13 (7)), stage one detector is more robust to pose variations while stage two detector is more accurate for well normalized images.

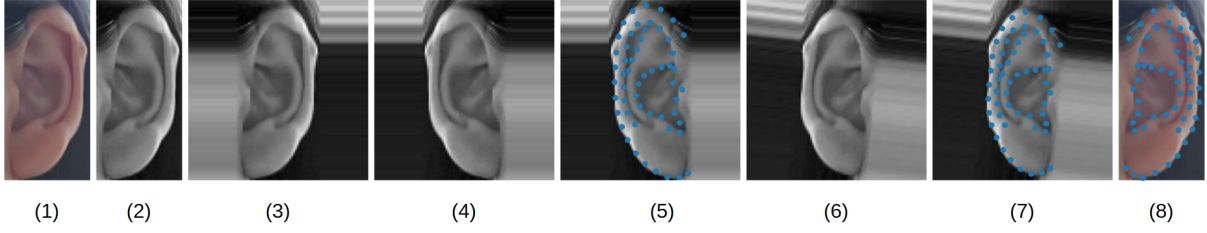


Figure 5.13. Example of our cropped ear landmarks localization based on Hansley et al. (58). (1) Cropped ear image, (2) Convert the image to grayscale, (3) Coarse parameter estimation and image normalization, (4) Side classification and flip if needed, (5) First stage landmarks detection, (6) Adjustments based on (5) and normalization, (7) Second stage landmarks detection, (8) Back-project landmarks to (1). The original frameworks contains step (1)-(7) while our pipeline drops step (4) thanks to the face alignment step and adds position mapping to support (8).

5.6.3 Triangulation

Once we have a series of anatomical ear landmarks as the point set, we need to structure the set to triangles for morphology and rendering. For a finite point set $V = v_1, v_2, \dots, v_n$ in the Euclidean space, the point-set triangulation is a finite collection T of d -simplices of V that satisfies: (1) The union of all these simplices equals convex hull of V and (2) Any pair of these simplices intersects in a common face (137). One popular method, called Delaunay Triangulation (94), subdivides each input image into a triangular mesh. For a set of ear landmarks P , Delaunay triangulation describes the connected triangles' vertices $DT(P)$ where no point in P lies within the circumcircle of any other triangle in $DT(P)$. An advantage to taking Delaunay triangulation is that it maximizes the smallest angles and avoids skinny triangles (117). However, the auricular zones should minimize anatomical-wise distortion in any transformation. When the landmarks are not well aligned with dividing vertices among different zones, the triangles should minimize the distortion of morphology for each auricular zone as much as possible. Based on that, we add another five control points derived from the original 55 landmarks. Fig. 5.14a shows a cropped ear with ground truth landmarks from "In-the-wild" ear database and its additional 5 control points. Compared to Fig. 5.3d, a_1 is roughly the tip of triangular fossa while $a_2 - a_5$ are

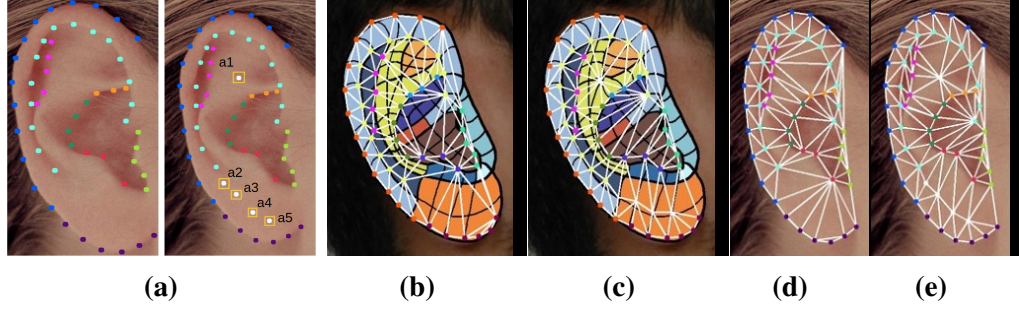


Figure 5.14. Ear crop and triangulation. (a) Cropped ear from “In-the-wild” ear database (193) annotated with (left) 55 ground truth landmarks and (right) additional 5 control points, (b) Delaunay method and (c) our method. Sample cropped ear with ground-truth landmarks that are triangulated by (d) the Delaunay method and (e) our method. The auricular zone maps from Fig. 5.10b.

proportional dividing points between antitragus and the lobule edge.

Then these triangular parts are warped and blended to produce the morph from the annotated template auricular zone maps to the detected ear image frames. Fig. 5.14 shows the images after triangulation. Compared to triangles from Delaunay triangulation (Fig. 5.14b), our triangles capture approximately similar regions in the recolored map (Fig. 5.14c). Thereby, our triangle list transforms the point correspondences to region correspondences much properly for a new image (Fig. 5.14d5.14e).

5.6.4 Ear Morphing and Alpha Blending

The triangulation step provides a triangle list T . With warping operation applied on each of the triangle T_i in T , we can blend I and J to M for each T_i . The amount of blending is controlled by the α paramter where

$$M(x,y) = (1 - \alpha)I(x,y) + \alpha J(x,y) \quad (5.1)$$

where $0 \leq \alpha \leq 1$

The steps go for each of triangle T_i in T :

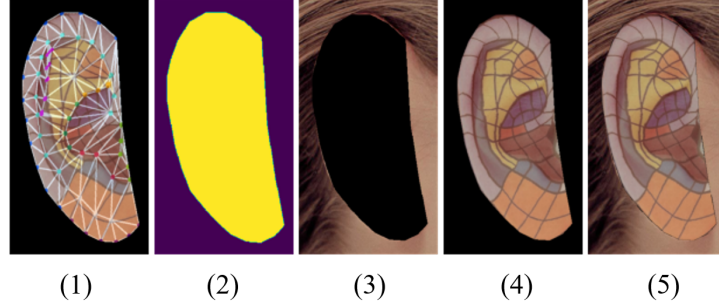


Figure 5.15. Ear morphing and alpha blending. (1) Result M after morphology with re-mapped landmarks and triangles, (2) Mask of M , (3) Foreground of the morphed image, (4) Background from the input frame, and (5) Final blended result.

- Calculate the affine transform that maps the (Ti_1, Ti_2, Ti_3) in L_I and L_J to that in L_M .
- Transform all pixels inside the triangle of I and J to the morphed image M .
- Alpha blend the triangle patches and save to M .

Fig. 5.15 shows the results of applying the above technique. The morphed image is a 70% blend of the input frame on the template mapping one. Since all the landmarks lie on the ear anatomically, the features are well aligned. Thus the triangles and the auricular zones are aligned as a result.

5.7 Experiments and Results

We designed experiments to validate each module in the pipeline. In the following parts, we present results for (1) the general application (Sec. 5.7.1), (2) facial acupoints localization (Sec. 5.7.2), and (3) auricular zone mapping (Sec. 5.7.3).

5.7.1 Application Screenshots

Fig. 5.16 shows the visualization of acupoints grouped by meridian channels in different poses. The machine learning model for face alignment described in Section 5.5 is robust against occlusions like glasses and finger pinpoints. As we separate the unit Cun system on the top of

Table 5.1. Acupoints categorized by localization times

Method	Direct	One-time Proportional	Multi-time Proportional
Reference points	0	4	0
Acupoints	38	16	15

the head from the frontal face with the hair segmentation, the acupoints covered by hair are also well localized.

5.7.2 Experiments on Facial Acupoints Localization

We set up an experiment to examine the accuracy of the system when localizing 4 reference points and 69 facial acupuncture points. Initially, we assign all the target positions into 3 groups by the localization complexity (see Tab. 5.1). As the system projects the target

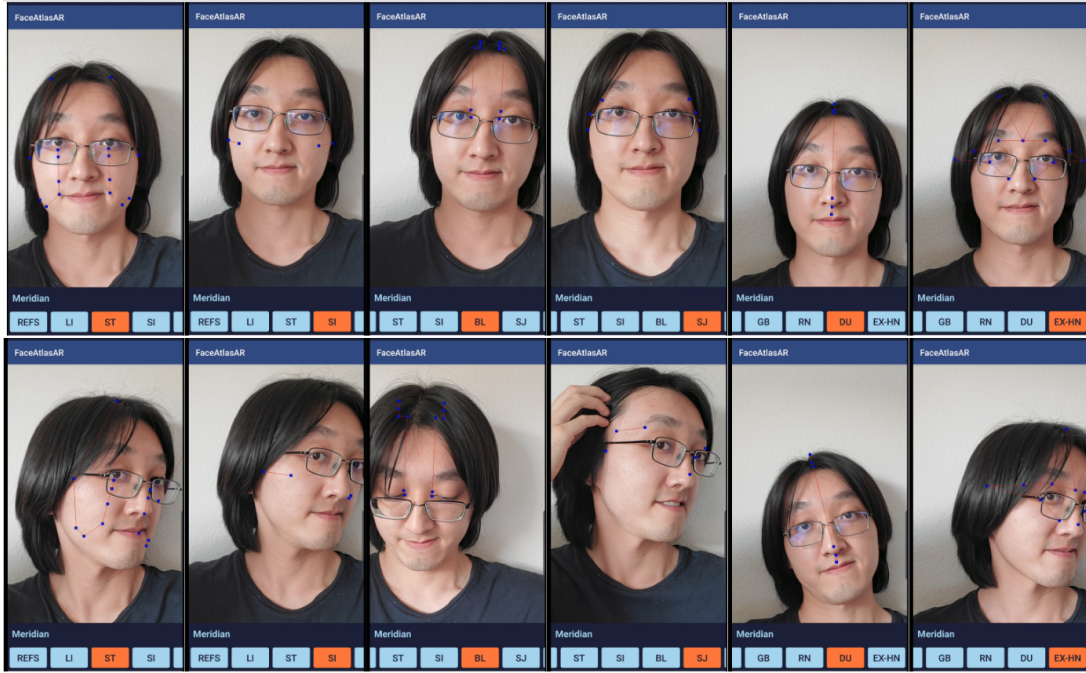


Figure 5.16. Android application screenshots for displaying acupoints grouped by meridian system in different poses.

acupoints generated with the B-cun method, users apply the palpation for tenderness method

to feel the precise target position as the ground-truth acupoint locations. The pictures captured from different angles make each target point measured five times. Although the system tolerates different angles adequately, a target point will be more well-localized when it faces straight to the camera without any angles, which is in line with our habit of looking into a mirror. Therefore, in our experiments, we captured pictures in typical usage scenarios (Fig. 5.16).

Referring to the metrics of the general face landmarks datasets, we analyze the following metrics: **Normalized Mean Error(NME, %)**:

$$NME(P, \hat{P}) = \frac{1}{M} \sum_{i=1}^M \frac{\|p_i - \hat{p}_i\|_2}{d} \quad (5.2)$$

The NME between the ground truth (P) and the predicted point ($\hat{P}$) coordinates for each image. M is the number of landmarks of each image; $\hat{p}_i$ in $\hat{P}$ is the i -th predicted landmark coordinates and p_i in P is the i -th ground truth landmark coordinates; d is the normalization factor. We adopt inter-pupil (eye to eye center) distance from the COFW dataset as the normalization factor.

Failure Rate (FR, %):

$$FR = \frac{1}{K} \sum_{k=1}^K [NME_k \geq 10\%] \times 100 \quad (5.3)$$

For one image, if NME is larger than a threshold (i.e., 10%), it is considered a failed prediction.

We measured the localization accuracies of target points, including 4 reference points and 69 acupoints, five times for each point. Fig. 5.17 polts the results as the distributions of normalized mean error.

The orange line indicates the threshold (10%) for the failed prediction. From the experiment results(Tab. 5.2), we found that the target points that require one- or multiple proportional methods for localizations are pinpointed less precisely than the ones with the direct method. Specifically, multiple times of proportional calculations that rely on the Cun system add inaccuracy to the results.

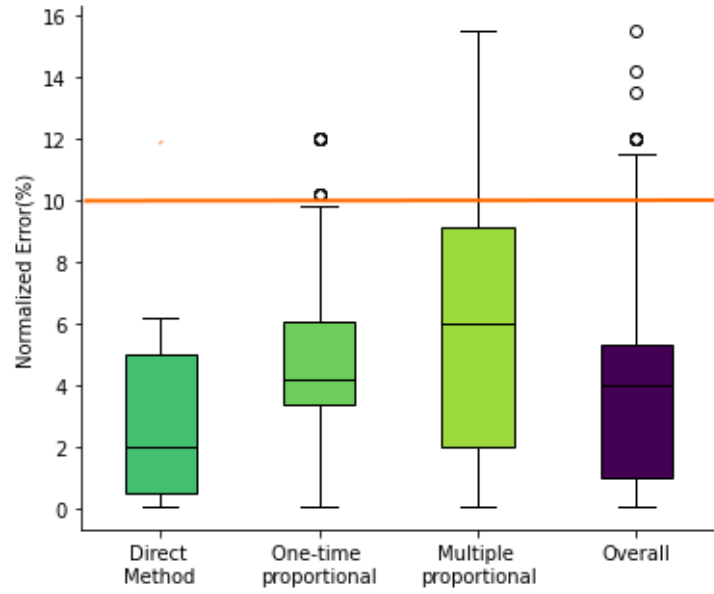


Figure 5.17. Distribution of normalized error for all target points.

Table 5.2. Evaluation of target points localization.

Category	NME	$FR_{10\%}$
Direct Method	2.64	0
One-time Proportional	4.97	9.0
Multiple Proportional	5.07	12.5
Overall	3.90	5.13

In summary, for facial acupoints experiments:

- Our system properly displays the requested acupoints on selected meridian channels.
- The system tolerates position offsets while enduring tilt and rotation.
- When the acupoints hide in one view, they will be visible and more accurate in another one.

For example, the frontal face hides acupoints in the ear region; thus, to view them around the left ear properly, the user needs to turn the head so that the left ear faces the camera.

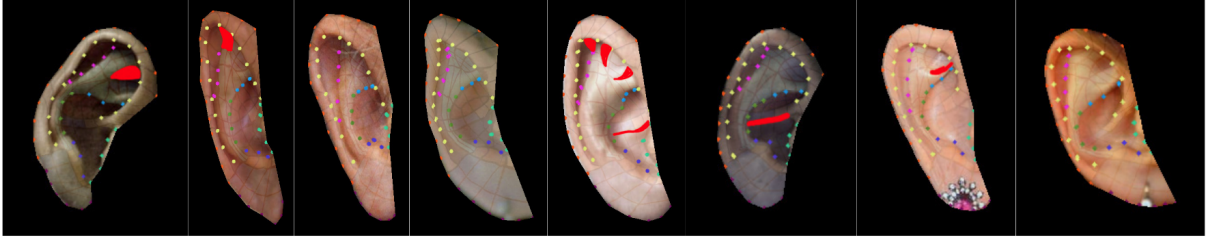


Figure 5.18. Sample annotated results from “In-the-wild” dataset.

5.7.3 Experiments on Auricular Zone Mapping

For auricular zone mapping, we evaluate our approach on two ear databases. One of them is the “In-the-wild” ear database (193) collected in the wild with ground-truth ear landmarks. The other one is AMI Ear Database (44) collected in the studio without landmarks.

“In-the-wild” Ear Database: Their ear images are in challenging environments such as heavily posed angles, significant lighting variations, notable occlusions, variant resolutions, and significant aging. The whole datasets are wildly collected, while our case prefers portraits shot by front cameras. Besides, the ears in their dataset are tiny in proportion to the image, making it hard to recognize detailed structures. Therefore, we filter out the pictures if their cropped ear image is less than a threshold ($(width + height) < 400pix$). We assess our system’s ability to work in different environments with torture-shaped ears with this database.

AMI Ear Database: The ear images are collected from 100 different subjects, each with the right ear in six poses (front, up, down, left, right, zoom) and one left ear image (back). Ground-truth ear landmarks are not available for this dataset, but their environment setup and lighting conditions are similar to our system requirements. Thus, it resembles the actual situation to explore the effects of the poses.

Despite the lack of manual gold standard, this experiment enables assessment of performance on a heterogeneous dataset. Fig. 5.18 and Fig. 5.19 present sample results from the two datasets. The red and green marks denote areas that failed to match the ground-truth annotations.

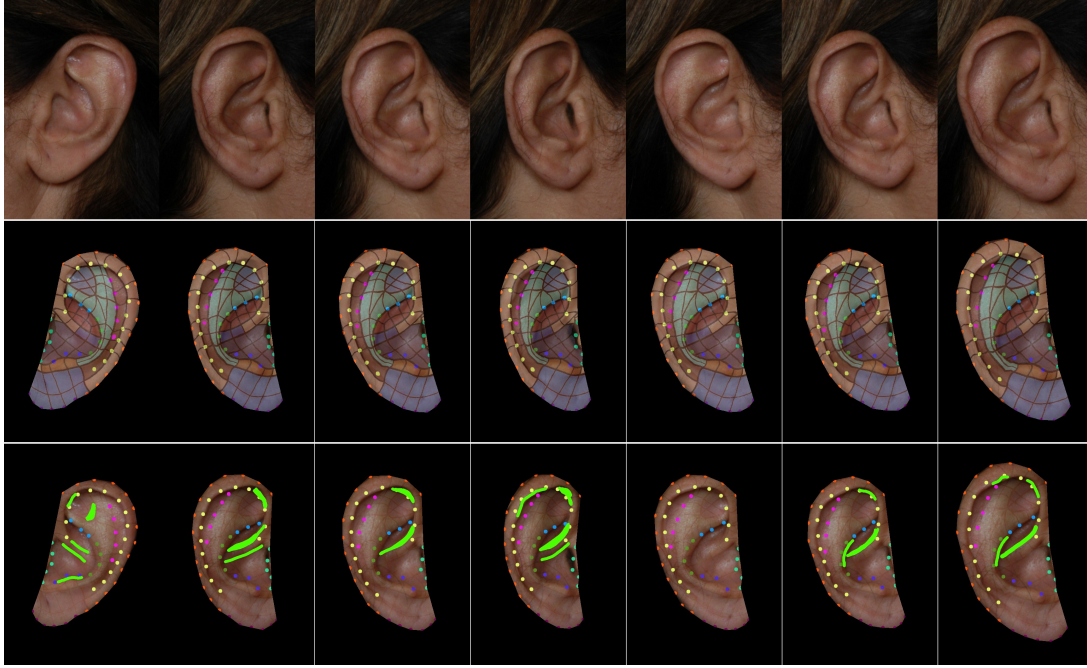


Figure 5.19. Sample annotated results from AMI dataset. Row 1 shows the original images, row 2 shows the resulting auricular zone maps, and row 3 labels failure areas of the results with green marks.

Fig. 5.20 analyzes the cumulative distribution function (CDF) on a percentage of incorrect predictions for the two datasets. It appears that performance on “In-the-Wild” datasets is much better than that on the AMI one. Out of 258 cropped ears in the “In-the-Wild” dataset, 67% images are accepted as completely correct mapping. Most incorrect mapping only affects up to 3% of the whole ear, meaning minor incorrect mapping in a zone may not affect other zones. For results on the AMI dataset, the percentage of false mapping is 2% – 12%, which indicates that offset labeling in a zone will ruin the adjacencies. Thus both areas are annotated as incorrect. Examples such as the first, second, and fourth columns in Fig. 5.19: compared to the results from the two datasets, the ground-truth anatomical landmarks provide accurate morphology.

An initial comparison between the two datasets shows that the system is robust to the lighting environment and occlusion. Comparably, poses are more inclined to decline the performance. We further evaluate the AMI dataset’s accuracy categorized by six poses based on the observations. Fig. 5.21 box plots the percentage of false area by categories. The back pose is

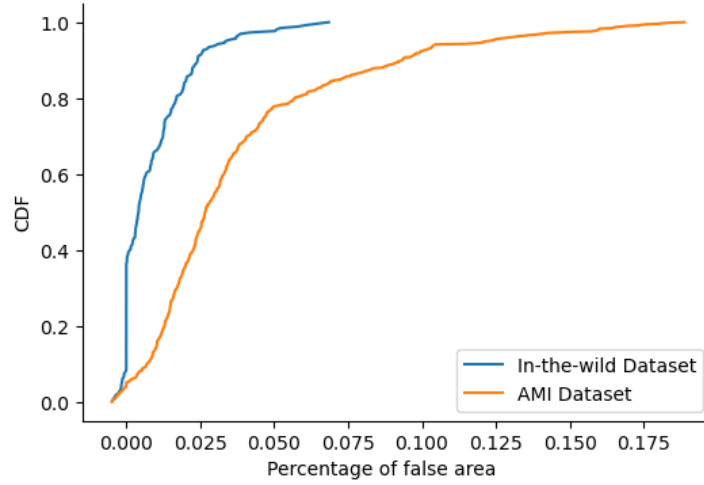


Figure 5.20. Cumulative distribution for “In-the-Wild” and AMI dataset.

a left-side profile, while others are right-side profiles with the individual facing forward (front), looking up and down (up, down) and looking left and right (left, right). The zoom category is also the right profile, with the subject facing forward but with a different camera focal length. Ideally, when users closely examine the right ear, they face the right ear straight to the front camera as much as possible. Thus, the right pose resembles the real settings the most. Other poses simulate occasions that are also likely to happen. The left pose relates to when both ears appear in the camera, making each of them partially occluded.

From the results, the ideal pose (right) suppresses most of the false percentages below 0.03 (3%). In contrast, the LEFT pose performs the worst (0.05 – 0.18) because the ears are usually not facing the cameras enough to get the model well-aligned. The system tolerates roll and pitch axes rotations, controlling the false area within 0.08.

Results on AMI indicate that without ground-truth landmarks, structures such as the Concha Cymba, Helicis Crus, and the triangular fossa are more likely to fail to match due to a lack of specific anatomical landmarks. Hence, we further adopt dice coefficients to measure

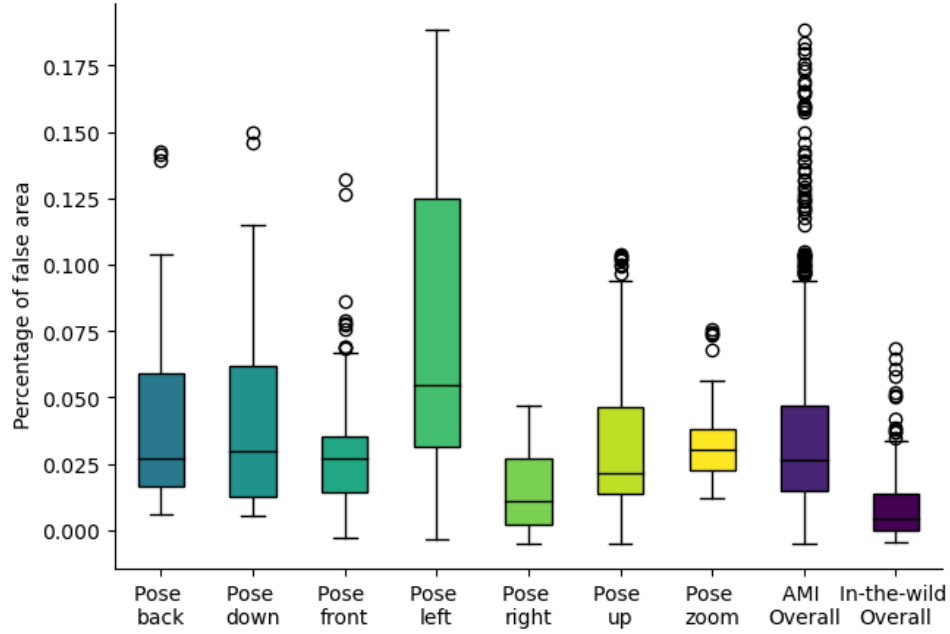


Figure 5.21. Percentage of the false area by categories. From left to right: 7 pose categories from AMI dataset, overall results in the AMI dataset, and overall results in the “In-the-Wild” dataset.

some structures of interest from the right pose images (Fig. 5.22):

$$\text{Dice Coefficient} = \frac{2TP}{2TP + FN + FP} \quad (5.4)$$

TP is the true positive, FP is the false positive, and FN is the false negative area. We use this measurement to focus on deep structures such as the Helicis Crus, Triangular Fossa, Anti Tragus, and Helix, which failed our initial experiment due to a lack of specific anatomical landmarks. Results show that more complex structures have higher rates of false estimation.

5.7.4 Performance

We compare the performance on a desktop with Nvidia GeForce RTX 2070 SUPER and a Samsung S10 cell phone. Tab. 5.3 shows the time on two devices respectively for 1) reading information from the file and setup the lookup table, 2) the average time for single acupoint

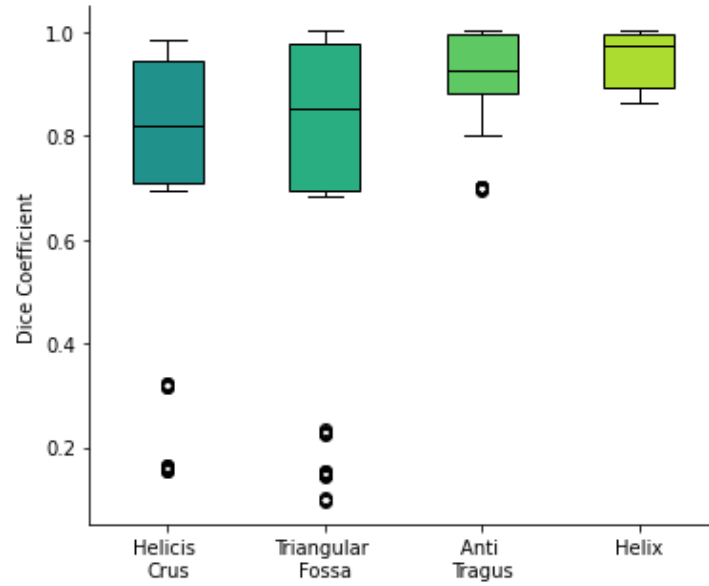


Figure 5.22. Dice coefficients for Helicis Crus, Triangular Fossa, Anti Tragus, and Helix.

Table 5.3. Application performance on a desktop and a mobile device.

Device/Time,ms	Setup from the File	Generation(Avg per Point)	Generation (Overall)
Desktop	0.102	0.45	32.93
Samsung S10	0.279	1.66	121.2

location generation, and 3)the overall time for generating acupoints.

In Fig. 5.23, we show the frame rates for five tasks on the Samsung S10: 1) face alignment only, 2) hair segmentation only, 3) face alignment together with hair segmentation (which includes 1 and 2), 4) overlaying facial acupoints (which includes 3), and 5) overlaying facial acupoints and auricular maps(which includes 4). Overall, it maintains ~ 30 FPS performance for generating and visualizing facial acupoints and auricular maps to be in real-time. Note that performance on auricular mapping was not measured alone because this process relies on the results from face alignment.

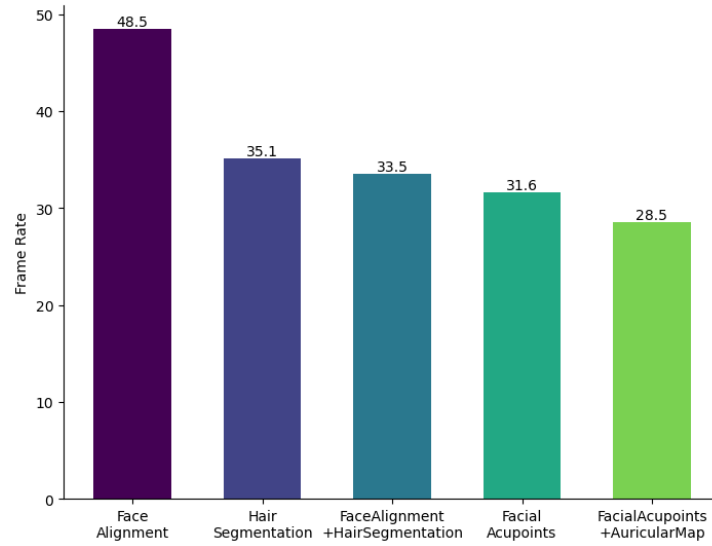


Figure 5.23. Average frame rates for different tasks.

5.8 Conclusion

In this paper, we proposed E-FaceAtlasAR, an extended end-to-end facial acupuncture assistance AR system. It overlays auricular zone maps and facial acupoints on users' faces interactively in real-time. The high accuracy of the estimation and the robustness empower users with little experience in acupuncture to pinpoint acupoints, thus assisting them in self-treatments like self-acupressure.

Future research should consider the potential effects of the proportional method more carefully. For example, multiple times calculation declines the localization accuracies. Further research is needed to investigate 3D interactions in different user scenarios. For instance, we could track users' hands/fingers while interacting with a target acupoint. Otherwise, external hardware, like acupuncture needles, can be applied for more precise interaction.

5.9 Acknowledgments

Chapter 5, is largely a reprint of the material as it appears in Zhang, Menghe, Jürgen P. Schulze, and Dong Zhang. "E-faceatlasAR: extend atlas of facial acupuncture points with

auricular maps in augmented reality for self-acupressure.” *Virtual Reality* 26, no. 4 (2022): 1763-1776. The dissertation author was the primary investigator and author of this paper.

Chapter 6

VR for Acupuncture? Exploring Needs and Opportunities for Acupuncture Training and Treatment in Virtual Reality

6.1 Abstract

Acupuncture is a form of medicine that involves inserting needles into targeted areas of the body and requires knowledge of both Traditional Chinese Medicine (TCM) and Evidence-Based Medicine (EBM). The process of acquiring such knowledge and using it for practical treatment is challenging due to the need for a deep understanding of human anatomy and the ability to apply both TCM and EBM approaches. Visual aids have been introduced to help understand the alignment of acupuncture points with key elements of the human body, and are indispensable tools for both learners and proficient acupuncturists. However, they are often not enough to enable effective practice and do not fully support the learning process. Novel approaches based on immersive visualization and Virtual Reality (VR) have shown promise in many healthcare settings due to their unique advantages in terms of realism and interactions, but it is still unknown whether and how VR can possibly be beneficial to acupuncture training and treatment. Rooted in participant observations and semi-structured interviews with eight doctors and nine students, we explore the needs and pain points of current acupuncture workflows at the intersection of EBM and TCM in China and the United States, and across the expertise spectrum.

We highlight opportunities for introducing VR in today’s acupuncture training and treatment workflows, and we unveil and discuss two design approaches that build on 11 specific challenges spanning education, diagnosis, treatment, and communication.

6.2 Introduction

Acupuncture (77) is an important form of alternative and integrative medicine that involves precisely inserting thin needles into targeted body areas. It has long been used in clinical practices around the world. The key component of acupuncture treatment is identifying and stimulating anatomic sites (*a.k.a.* acupuncture points, or acupoints).

Compared to general medical practices, acupuncture treatment and training face unique challenges. Unlike Western medicine, acupuncture relies on the practitioner’s experience in comprehending the intricate interplay between human anatomy and the overall health of the patient in a holistic manner, drawing from the principles of Traditional Chinese Medicine (TCM) (174). Additionally, to ensure effective and safe treatments, it also requires expertise in Evidence-Based Medicine (EBM), which integrates the best available scientific evidence with clinical expertise and patient values. However, combining the principles of TCM with EBM approaches can be challenging for novices without practical experience in understanding these intricate connections. Moreover, acupoints are not precisely described in anatomical terms due to limited research on the underlying mechanisms. This presents a challenge in ensuring consistent quality of care. Furthermore, the current acupuncture training process heavily relies on texts and atlases that do not fully capture the three-dimensional nature and intricacies of real-world human anatomy.

Virtual reality (VR) has emerged as a promising solution for diverse medical contexts (102) and medical training programs (121; 134; 110) due to the unique advantages of natural perceptions of 3D information and the support for more intuitive interactions. While a few existing products, such as AcuMap (107), have made attempts to integrate acupuncture

training workflows into virtual reality, it is still unclear *why* and *how* the VR can effectively facilitate acupuncture treatment and training workflow.

Therefore, in this work, we take one step back and focus on investigating the benefits of using VR to enhance acupuncture treatment and training workflows, including understanding the specific needs of practitioners and students. By conducting semi-structured interviews with eight acupuncture doctors and nine students from professional medical institutes located in China and the United States, we identified 11 challenges spanning education, treatment, and cooperation. We present our initial insights and discuss design opportunities to address the challenges identified by participants across three levels of expertise, encompassing both training and treatment. Through this process, we identified three guiding themes that apply to both aspects: the acquisition of fundamental knowledge, the accumulation of clinical experience, and the facilitation of demonstration and collaboration.

In summary, this chapter highlights two main contributions to the field of Human-Computer Interaction (HCI) and the design of Virtual Reality systems for acupuncture training and treatment:

- **Need-Finding.** Through a need-finding process, we reveal the challenges faced by acupuncture students and practitioners in their daily routines.
- **Design Considerations.** We propose two potential design patterns for VR systems to address the challenges emerged in our need-findings.

We believe that the findings generated by this work will offer critical insights to inform future researchers and practitioners who are attempting to design and develop collaborative VR applications in support of acupuncture training and treatment workflow.

6.3 Background and Related Work

In this section, we first introduce the acupuncture training and treatment processes. Then we give an overview of the literature on immersive visualizations in Virtual Reality (VR) and

how this is applied in medical fields, especially focusing on acupuncture.

6.3.1 The Acupuncture Training and Treatment Process

Traditional acupuncture, a TCM practice dating back thousands of years, is founded on the principles of the Meridian Theory (162), as outlined in the ancient text *The Yellow Emperor's Classic of Internal Medicine* (169). The two key concepts of this theory are meridian and acupuncture points (or acupoints). Meridian is a network of energy pathways that run throughout the body, where the life energy (called *qi*) flows. Acupoints are the specific points lying on the meridian where the *qi* converges and transfers. Acupuncturists in ancient times healed patients through the proper stimulation of acupoints.

Adapted from traditional acupuncture, current Medical Acupuncture (174) incorporates knowledge of anatomy, physiology, pathology, and the principles of EBM. Despite the unclear link between TCM acupoints-meridians and gross anatomy, the WHO standard (175) uses modern anatomical terms to describe acupoints and meridians. Nowadays, medical acupuncturists often work closely with other healthcare providers to provide integrated care. This integration of Western and Eastern practices has allowed practitioners to develop new and effective treatment methods that target anatomical structures and nerve pathways directly to produce specific physiological effects, such as reducing pain or stimulating the immune system (174). Accordingly, innovative acupuncture modalities arose, such as scalp acupuncture (59), eye acupuncture (150), auricular acupuncture (173), and wrist acupuncture (194).

Throughout history, acupuncture education has maintained a holistic approach while placing emphasis on cultivating a comprehensive understanding of the human body (169; 175). In modern times, acupuncture education institutes have further developed their programs to incorporate a more detailed understanding of human anatomy, physiology, and pathology, complementing the traditional holistic principles of ancient acupuncture practices (174). However, acupuncture education poses unique challenges, as it is still more conventional and traditional, and lacks some of the resources and technological advancements found in Western medicine (30).

Furthermore, the fundamental differences between TCM and EBM make it more difficult to integrate the diagnosis, treatment, and explanation of TCM and EBM in education (64).

A typical acupuncture treatment begins with an initial consultation and physical examination, during which the practitioner assesses the patient's health history, current symptoms, and overall situation. The practitioner then inserts thin needles into specific points on the patient's body to elicit the patient's sensation (called "de qi"). The practitioner may further provide recommendations for self-care or follow-up appointments and adjust the treatment plan as necessary. Using needles to stimulate specific anatomic sites is the core step in the treatment. Strategic needle insertion into specific anatomic sites is a crucial component of acupuncture treatment. Although generally considered safe, even slight inaccuracies during needling can lead to unintended bleeding or organ puncture (171). As a result, novice practitioners may struggle to locate and insert needles correctly, potentially resulting in ineffectiveness or harm to patients. Further, individual differences in anatomy and sensitivity to stimulation can make precise needling more challenging (100).

6.3.2 Virtual Reality in the Medical Field

VR technology has been widely adopted in the medical field for various applications, including diagnosis (101), surgical planning (15; 182; 31), and therapy (102; 43), offering new opportunities for training and education (121; 134).

With VR, medical professionals can interact with 3D models of CT scans, MRIs, and other medical images in a more immersive and intuitive way (130). For example, visualization of 3D medical structures in radiotherapy treatment in VR significantly improves precision and reduces mental load and effort (26; 27). VR therapy has shown promising results in treating conditions such as post-traumatic stress disorder (PTSD) (50), chronic pain (74; 52), and offers progressive support with meditation (45). Advancements in VR have opened up new avenues for medical collaboration in many different scenarios, allowing healthcare professionals to work together in immersive virtual environments (86; 168). For surgical planning, it allows surgical

teams to understand the spatial relationships among internal structures and plan out complex procedures in advance (120; 10; 31). It's also evaluated to support emergency medical teams with interactive checklists and more generally dynamic cognitive aids (177).

In education, VR has been shown to enhance performance and engagement, resulting in improved retention of information compared to traditional learning methods (87; 71; 135). Medical imaging in VR provides a detailed and accurate representation of anatomical structures, particularly in cases of complex or subtle anatomy, such as cardiac anatomy in medical education (111). VR technology has been increasingly accepted to simulate patient-based procedures (111; 56) and is also being recognized to improve cadaveric temporal bone dissection performance when compared with traditional teaching methods (191).

As acupuncture becomes increasingly important in the medical field, there is growing research and development focused on using VR technology to improve the effectiveness of acupuncture treatments as well (99). Early-stage research constructed 3D digital human models integrating meridian and acupoints (61; 76). However, their training systems and methods are primarily rooted in ancient theory and practice, which imposes limitations on the depth of anatomical understanding. To address these limitations, advanced VR training systems have been developed, leveraging detailed 3D anatomy for enhanced learning experiences (28). For example, a study at the Guangzhou University of Traditional Chinese Medicine used a virtual acupuncture teaching system to demonstrate meridian outlines, acupoint anatomy, and needling techniques (138). One notable company that focuses on making VR solutions for general medical training experience is MAI (108). In 2021, they commercialized AcuMap (107), the world's first VR training solution for acupuncture that incorporates anatomy, meridians, and acupoints on the virtual human model. Another recent trend in VR acupuncture research focuses more on exploring 3D user interactions made possible by the development of gesture recognition (188), face alignment (185; 187), and full-body tracking (39), pushing the training scenarios from virtual reality to mixed reality (146; 178). While recent acupuncture research has utilized x-rays, neuroimaging, and ultrasound to standardize the identification of acupoints (82), locate new

needling sites (23), and investigate safety in terms of needling depth (100), there is still a lack of widely available medical imaging visualization tools specifically designed for acupuncture treatment and research.

In summary, the existing research and commercial landscape shows how current VR products for acupuncture are primarily based on standard 3D anatomy models for training, which are adapted from EBM anatomy education, rather than designed with acupuncture domain experts. This creates an important gap and an opportunity to investigate whether these designs are suitable for acupuncture students and what features may be lacking. As medical acupuncture relies on evidence-based principles, it is important to also explore how should VR applications for acupuncture education and clinical use incorporate actual human data in addition to relying on standard 3D models.

Our need-finding study aims to understand the current needs and pain points in acupuncture training and practice and explore the role that VR technologies could play in addressing those challenges. Our overarching goal is to enable the design of effective systems that integrate key elements that have not yet been outlined by existing work into an increasingly universal acupuncture practice that spans TCM and EBM.

6.4 Methods

Our study is rooted in semi-structured interviews and participant observation. We first conducted observations of acupuncture treatment and tutoring workflows and then engaged in semi-structured interviews with acupuncture students and doctors. This user-centered design (24) approach allowed us to facilitate an in-depth understanding of the barriers that acupuncture practitioners face in their daily routines. The study was approved by the local Institutional Review Board (IRB).

ID	Country	Gender	Age Group	Status*	Years of Acupuncture Education/Treatment Experience	VR Experience**	Interview Method	Interview Length (min)
D1	CN	M	25~34	L.Ac.	6~10	L1	Online	61
D2	CN	F	35~44	L.Ac.	11~20	L1	Online	69
D3	CN	M	25~34	L.Ac.	<2	L3	Online	59
D4	CN	M	35~44	L.Ac.	11~20	L1	Online	52
D5	US	F	55~64	L.Ac.	>20	L0	Online	55
D6	US	M	35~44	L.Ac.	<2	L2	In-Person	70
D7	US	M	55~64	L.Ac.	11~20	L1	In-Person	55
D8	US	F	35~44	L.Ac.	<2	L0	In-Person	63
S1	US	M	35~44	Student	1~2	L1	Online	50
S2	US	F	25~34	Resident	4	L2	Online	65
S3	US	F	35~44	Student	1~2	L1	Online	63
S4	US	M	35~44	Student	1~2	L1	In-Person	57
S5	US	F	>65	Student	3	L1	In-Person	58
S6	US	F	35~44	Resident	4	L1	In-Person	52
S7	US	F	25~34	Student	3	L1	In-Person	56
S8	US	F	35~44	Student	3	L1	In-Person	68
S9	US	F	35~44	Student	1~2	L3	In-Person	65

* L.Ac. is the abbreviation for Licensed Acupuncturist

** VR Experience levels: L0-"I don't know anything about AR/VR.", L1-"I've heard about AR/VR and know what these are, but I never get a chance to try it out.", L2-"I've tried it out once or twice before.", L3-"I frequently used them for games, movies, etc.", and L4-"I consider myself as an expert for these."

Figure 6.1. Demographics of the recruited participants, including eight acupuncture *Doctors* and nine *Students*.

6.4.1 Participant Recruitment

We recruited 17 domain-expert participants with different experience levels, including eight doctors and nine students (see Fig. 6.1). The participants were recruited from five professional acupuncture institutes, including three teaching hospitals, one private group clinic, and one individual clinic.

We recruit participants from both China and the United States. China is where acupuncture first developed and has a rich history dating back thousands of years. Chinese acupuncture was the first form of Traditional Chinese Medicine (TCM) to actively seek integration into Western medicine (175). In the United States, acupuncture is recognized as a primary care modality and is increasingly being incorporated into mainstream medical care. Studying the practice of acupuncture across China and the United States allows us to examine how it is integrated into the Western healthcare systems and to investigate its effectiveness and potential applications in this context, yielding a more comprehensive and holistic understanding of the practice and its potential benefits.

6.4.2 Participant Observation

The workflow observations were conducted three months before the interview to get familiar with the workflow of acupuncture, as well as to prepare the questions for the interview round. We observed one treatment session in a private group institute in China and five treatment sessions in a teaching hospital in the US with the treatments given by both interns and licensed practitioners. Two of the researchers also underwent acupuncture treatment to better understand the patient-side of the workflow. Most of the treatment sessions lasted around 50 minutes, with a few shorter ones lasting around 30 minutes. For a typical treatment observation, we entered the clinic room with the doctor's and patient's consent and stood by to observe their conversation and physical diagnosis. Although we were not allowed to record any images or videos, we can take notes. When the doctor asked the patient to prepare for the treatment, we left the room with them and observed them discussing with their advisors or colleagues. When time permitted, we were allowed to ask questions. Afterward, we followed the doctor back to the clinic room and observed them placing needles and administering other treatments to the patient. Finally, when the acupuncture needle retention time was over, we all exited the clinic room and discussed any questions we might have had about the observation.

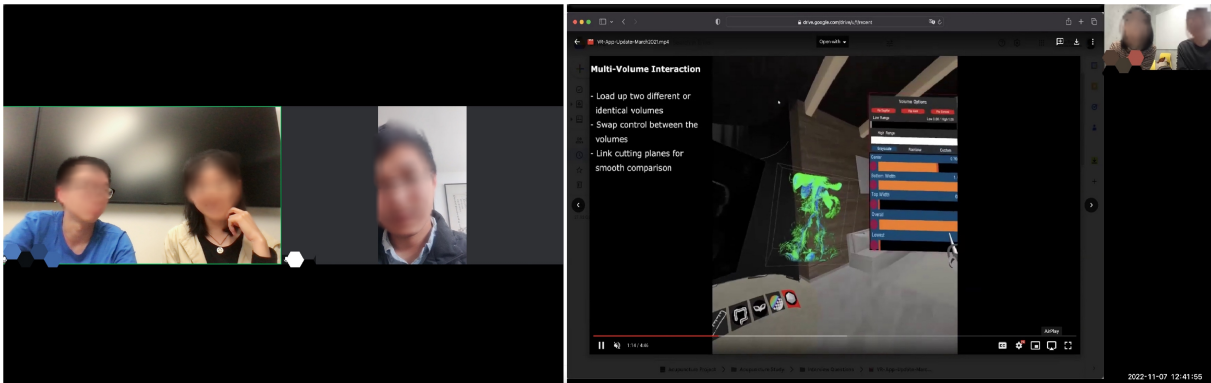
6.4.3 Semi-structured Interviews

We individually conducted interviews with all 17 participants, with each interview taking 55 – 65 minutes. Since we wanted to also root our investigation into the potential of using VR immersive technology in acupuncture, we encouraged the candidates to participate in person so that we could expose them to a first-hand VR experience (see below Sect. 6.4.3 on using a cultural probe).

Pre-Screening Questionnaire — To address the complexity of acupuncture and its intersection with people's cultural, professional, and social backgrounds in the US (30), an online pre-screening questionnaire was developed. This enabled a more thorough understanding of the



(a) Photos from in-person interviews.



(b) Screen shots from online interviews.

Figure 6.2. Settings of (a) in-person, and (b) online interviews. (a) Left: Designer and participant in the conversation. (a) Right: A participant is exploring a VR medical application as part of our cultural probe exposure. (b) Left: Designers and a participant in the online video conversation. (b) Right: Designers are illustrating the VR medical application over the pre-captured video as part of our cultural probe exposure.

participants before conducting interviews, allowing for relevant topics to be discussed in greater depth. The questionnaire, detailed in Appendix A.1, includes 12 multiple-choice questions and aims at collecting the following data:

- Demographic information.
- Expertise level in acupuncture.
- Frequency of various collaborations in their daily routine.
- Use of medical imaging in their practice.
- Experience with VR/AR.

Remote and In-person Interviews — The semi-structured interview topics were divided into *Student* (S, See Fig. 6.3a) and *Doctor* (D, See Fig. 6.3b) topics and were kept consistent within the group. We collaboratively designed the interview topics with experienced TCM doctors, who helped us frame them in professional terms grounded in acupuncture practices. Since the participants had noticeably unique backgrounds, we encouraged them to tell us about their exclusive experiences by using open-ended guiding questions and adjusting our questions while adapting to the conversations.

All interviews were video/audio recorded with participants' permission and transcribed for further analysis. Then two researchers analyzed all interviews using inductive and deductive coding approaches and generated specific codes from the collected data using grounded theory (158). We then examined and grouped the codes and concepts to describe the findings in Sec. 6.5.

VR Cultural Probe —

In general, our study looked at need-finding to then identify opportunities for new technologies, but we also wanted to get some direct feedback from participants on VR as a possible new paradigm in acupuncture. Since our participants had diverse experiences with

ID	Themes	Goals	Topics	Sample Guiding Questions
S-T1	Personal Background	Warm-up and decide the most relative topics to the participants	General background	• What led you to the TCM school (background)?
			General experience reflection	• In general, what's the best and the most challenging thing as a TCM/acupuncture student?
S-T2	Typical Practice	Understand the pain points for the TCM and acupuncture students.	Learning fundamental knowledge	• How did you associate anatomy knowledge with acupoints location when you had the classes? What are the major barriers? Any difference when you were in/observing clinics? • What tools have you used to help you learn? Which one so far do you like the best? What features you want but unavailable?
			Gaining clinical experience (Diagnosis and decision making)	• What objective information is emphasized to collect before the treatments in the classes? Did you find any difference in/observing clinics? • How do you learn to use medical imaging? In what ways do you integrate it with acupuncture? What are the major barriers?
S-T3	Collaboration and Communication	Understand the barriers in their daily collaborations and communications.	Student-patient communications	• Describe a typical situation where you handle patients on your own. In which aspect do you feel the least confident? What are your strategies when this situation happens?
			Student-Doctor communications	• Describe a typical scene you're with your supervisor in clinics. What questions did you ask the most in/after your observations? Is there any problem/improvement when you think back?
VR Demo as the Cultural Probes				
S-T4	Virtual Reality for Acupuncture	Explore the design opportunities for the doctors.	VR for acupuncture	• How could VR benefit acupuncture? • What are the possible features/information that might particularly accelerate your learning process?

(a) **S** stands for Student and **T** stands for Theme; we use **S-T#** to indicate themes for students, e.g., S-T1 is the first theme discussed with students.

ID	Themes	Goals	Topics	Sample Guiding Questions
D-T1	Personal Style/Background	Warm-up and decide the most relative topics to the participants	Career background	• Can you tell us your career path to TCM and acupuncture?
D-T2	Typical Practice	Understand the pain points for the acupuncture doctors in their daily practice.	(Integrative) Diagnosis and decision making	• What types of patients you usually deal with? Which part do you think could easily make mistakes. • What objective information you usually collect? Are there any other materials you find valuable but often lack access to? • We read that some people focus on acupuncture standardization. What do you think of that? If positive, in what aspects do you think they can be first standardized and drop for standardization (e.g. Choice of acupoints, depth, needle size...etc)? If negtive, why? • How do you use medical imaging in your practice? How does medical imaging affect your decisions?
D-T3	Collaboration and Communication	Understand the barriers in their daily collaborations and communications.	Doctor-doctor collaborations	• How do you share the treatment plans with other doctors? How does it usually work?
			Doctor-student communications	• What do you think is the hardest part for a student to follow your instructions?
			Doctor-patient communications	• Do you discuss your treatment planning with patients? Did you find any difficulties? What concerns do patients usually have?
VR Demo as the Cultural Probes				
D-T4	Virtual Reality for Acupuncture	Explore the design opportunities for the doctors.	VR for acupuncture	• How do you think VR could benefit the acupuncture? • What are the possible features/information that might be particularly useful for your practice?

(b) **D** stands for Doctor and **T** stands for Theme; we use **D-T#** to indicate themes for doctors, e.g., D-T1 is the first theme discussed with doctors.

Figure 6.3. Themes and guiding questions for students and doctors.

VR or AR (see Fig. 6.1), we felt that this might bias their reflections on VR applications and their opinions about a completely new use of a technology applied to their well-established acupuncture experience. We, therefore, introduced a cultural probe (36), to help with this process and allow participants to familiarize with VR technology while inspiring new design opportunities. To reduce bias in terms of need-finding, the cultural probe was only introduced at the end of the interview.

For our cultural probe, we showed MAI's AcuMap demo video (109) and an existing VR application for surgical planning (186) (see Fig. 6.4). We introduced them to VR by showing the footage of AcuMap, usually 40 min into the interview. After an initial discussion over the video, we moved to the medical imaging-based surgical planning VR application (186). For the in-person interviews, we first demoed the application while illustrating each functionality. We then allowed them to explore the visualization and 3D interaction in the application themselves. For the online interviews, we played a pre-recorded demo video and provided explanations for each operation and feature as it played.

Final discussions took place after the demo session. After the discussion, we asked about their opinion and investigated their attitudes toward the VR experience for medical imaging. If they were positively engaged, we dived deeper into possible ways to empower them with VR technology during acupuncture education and practice by asking specific questions related to VR for acupuncture (S-T4 or D-T4 questions).

6.5 Findings

In this section, we examine the challenges and needs that emerged during our need-finding study and the opportunities to introduce immersive VR technology to support acupuncture practice. Given the diverse profiles and needs of our participants, we will discuss findings from the perspective of (i) early-stage students, (ii) residents and novice doctors, and (iii) experienced doctors. Insights generated by specific doctors are referred to as [D1]-[D8], while we refer

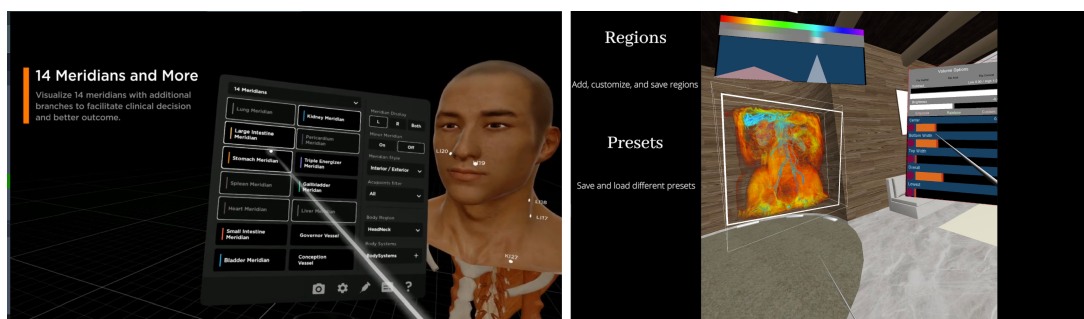


Figure 6.4. Cultural probe materials. (Left) A screenshot of MAI’s AcuMap demo video showing a partial standard 3D human anatomy model with selected meridians and acupoints. (Right) A screenshot of the VR surgical planning application showing an anonymized MRI data volume with a visualization toolbox.

to students’ insights using [S1]-[S9]. Fig. 6.5 summarizes our findings and categorizes them into three themes: Learning Fundamental Knowledge (T1, Sect. 6.5.1), Accumulating Clinical Experience (T2, Sect. 6.5.2), and Demonstration and Collaboration (T3, Sect. 6.5.3).

6.5.1 Learning Fundamental Knowledge

Almost all students described their first 1-2 year experience as struggling, overwhelming, and sometimes even crazy. They felt overwhelmed by the amount of information they had to memorize and understand, including knowledge of both TCM and EBM. This is because their supervisors emphasized the importance of “*learning the fundamentals as precisely as possible.*” [D1]. We outline four overall challenges in the setting of learning fundamental knowledge below.

[T1-C1] Lack of efficient ways to associate 2D text/image descriptions with 3D human anatomy

While demonstrating their arguments, we found that participants wanted to use their past learning experiences or re-enact some of their clinical cases to explain their issues. It was interesting to witness how they struggled when trying to construct 3D anatomy structures in their heads to be able to explain. As an example, S4, a student in his second year of study, highlighted that his current challenge is grasping the anatomical positioning of acupoints in relation to the

ID	Topics	Theme	Challenges	Impacts*		
				Early-stage students	Residents and novice doctors	Experienced doctors
T1	[Fundamental] Learning fundamental knowledge	S-T1 S-T2 D-T3	T1-C1 Lack of efficient ways to associate 2D text/image descriptions with 3D human anatomy	✓	✖	✖
			T1-C2 Difficulty to associate TCM acupoints and meridians with anatomic structures	✓	○	✖
			T1-C3 Imperfect methods to assess localization and corrections	✓	○	✖
T2	[Experience] Accumulating clinical experience	S-T2 D-T2	T2-C1 The gap between working with real human bodies and the standard models learned in class	✓	○	✖
			T2-C2 Lack of support for hands-on and real-world needling and palpation practices	✓	○	✖
			T2-C3 The limited view of what is happening beneath the skin creates safety concerns	✓	✓	✓
			T2-C4 Difficult matching between Western medicine diseases and TCM principles and practices	N/A	✓	✖
			T2-C5 Expanding opportunities for medical images in acupuncture	N/A	✓	○
T3	[Cooperation] Demonstration and Collaboration	S-T3 D-T3	T3-C1 Need for better supports to discuss treatment plans with supervisors	N/A	✓	✓
			T3-C2 Lack of tools to discuss integrated plans across EBM and TCM	N/A	✓	✓
			T3-C3 Challenges of explaining treatments to patients and demonstrating results	N/A	✓	✓

* To qualitatively assess the effects of a challenge on a specific group of participants, we use a four-point scale: '✓' for a 'great impact', '○' for 'some impact', '✖' for 'less impact', and 'N/A' for 'not applicable'

Figure 6.5. Overview of challenges emerging from acupuncture doctors and students across four categories. Refer to Fig. 6.3b and 6.3a for the theme indices.

first and second ribs. As a former nursing student, he felt that his previous education of the human body was too compartmentalized:

“I never considered everything so three-dimensional, like the depth of the skin and the tissue and layers, and thinking about how organs interact with one another.” [S4]

Their supervisor, D6, an experienced acupuncturist, stressed the importance of *thinking in 3D* for early-stage students: *“students need to think of the acupuncture points and the meridian system as a 3D concept, not 2D. How shallow the lung is, how deep the kidney is, and how many layers of muscles are there before the needling”*.

Despite the crucial role of understanding 3D concepts in acupuncture, many students still rely solely on 2D resources such as textbooks, with even digital companion apps being limited to a 2D format. During the interview, S1 pulled a piece of paper with a stick figure of a foot, pinpointing several acupoints: *“I was practicing annotating the acupoints with my chart. It’s like a coloring book, and that’s what I usually do”*. While some students reported benefits from using 3D anatomy education apps (14; 148), none were specifically designed for acupuncture

learning:

“When it comes to TCM materials, they are just 2D illustrations and written descriptions.” [S6].

Therefore, none of the participants were able to identify an application that effectively demonstrates acupoints and meridians in a 3D context.

[T1-C2] Difficulty to associate TCM acupoints and meridians with anatomic structures

Accurately locating acupoints based on anatomy was identified as the biggest challenge among entry-level participants.

The primary reason we discovered is the separation of TCM and EBM, specifically the use of acupoints and channels in TCM, and the lack of a clear correlation between these concepts and modern anatomical understanding. For example, S8 observed how *“The difference between how western medicine and TCM see organs [...] livers, kidneys, heart spleen are not necessarily organs referred to in western medicine.”* S2 shared the same opinion and mentioned, *“Learning them both is almost thinking with two minds, but they’re never really separated”*. Students with Western medicine backgrounds, Like S9, mentioned how *“My previous knowledge helps me ease some stress of the overwhelming components of this program”*. However, as TCM emphasizes more on integrating the anatomical order and the organ system, linking new TCM knowledge with EBM concepts sometimes means *“rewiring my brain, because the mind was always thinking Western”* [D5]. Furthermore, integration of EBM and TCM practice requires *“a deep level of understanding beyond memorization, of the connection between the theories”* [S8]. Such integration affords new opportunities. However, today’s educational support is not on par. Students perceive a significant disparity between the way knowledge is illustrated in EBM and the lack of support to learn TCM materials. As a student graduating soon, S2 could still vividly remember the feeling in her first year:

“I remember oftentimes, I would close my eyes to visualize where the meridians would go on the body... So what I was missing is the visualization of the nerves and the meridians in a very clear way” [S2].

To further investigate why it's so vital to see both the visible anatomical structures and invisible meridians, an experienced doctor, D1, who recognized the great importance of acupuncture standardization, explained: *"Visualizing the relationship between acupoints and anatomical structures is crucial for achieving reproducibility in treatment plans."* S3, who grew up in a family with a long-standing reputation for practicing TCM, commented how it used to take a very long time for someone to become a skilled acupuncturist because of the lack of efficient ways to understand anatomy precisely. So she believes that *"the high precision correlation between acupoints and anatomy in acupuncture makes it efficient to cultivate remarkable acupuncturists."*

[T1-C3] Imperfect methods to assess localization and corrections

Early-stage students are trained with palpation skills to identify the acupoints on the surface skin before any needling practice. However, they often face challenges in determining the correct acupoint locations. They lack methods to assess the accuracy of their localization, which can impede their progress in training to become skilled acupuncturists. The main reason is the limited resources available in training. For example, S5 commented on challenges to be precise and improve the performance: *"It really takes a long time to get the point locations. You have to rely on the once or twice-a-week lab experience to know if you're on the right spots and have the memorization"* [S5].

While gaining precision in acupoint localization requires practice, feedback is a crucial aspect of this process. Without regular engagement with experts and instructors, students lack the guidance and direction necessary to make constant improvements in their skills. The limited interaction with experts and instructors can hinder the progress of students. Students are eager to learn faster and are hoping to have interactive applications to support them: *"I think it could be beneficial if it [3D Anatomy] could provide an interactive experience and people can play and learn"*, said S2, who is a big fan of using phone anatomy applications, but complained about their lack of interactive components. S4 confirmed how *"We use stickers and probes to practice, and you can see how big a sticker is compared to a needle. Even so, it's still hard to tell if the*

stickers are on the right spots”.

6.5.2 Accumulating Clinical Experience

[T2-C1] The gap between working with real human bodies and the standard models learned in class

Exposure to the clinics as assistants in the early stage is believed to contribute heavily to students’ performance. Students cherish their observation sessions as opportunities to engage in diagnosis and treatment procedures with experienced acupuncturists and begin to formulate their own assessments. S5 said, *“The observations let me know [that] the physical examination involves more than just identifying the anatomical location; it also involves understanding how the body feels and functions at various points”* [S5]. While those observation sessions are informative, some students outlined how they wished they could get more hands-on practice beyond that:

“There’s such a long leading time to being able to actually work with real people in clinics, you don’t [have the chance to] do it until much later. There’s a limitation to how much you can do before then” [S4].

While Western medical schools commonly introduce early-stage students to autopsy training as a means of improving their understanding of human anatomy and pathology, TCM educational practices, both in the US and China, lack such resources and opportunities. As pointed out by D1, a doctor from China: *“not every student will have a chance to attend a cadaveric training session”*. Similarly, in the US, *“only a small portion of students will consider taking a cadaver-based training program from a western medical institute after getting an acupuncture license”* [D6]. One such example in our participants’ cohort was a novice doctor D8, who finished her cadaveric training program 1-2 years ago, and confirmed its validity and importance, pointing out also how *“from the experience of cadaver training, the most stunning fact is the variation [of circumstances and] of individuals.”* In our interviews, we uncovered how it is common for students to be surprised by the difference between the real human body and the standard anatomical model they learned on, as confirmed by student S8:

“Everything we’re learning in school is just basis and foundation. The clinic is very different from the textbook in class and your exams because no patient is going to present themselves exactly like that.” [S8]

Even current visual aids do not seem to help bridge the gap; for instance, when we showed participants the AcuMap video as a cultural probe, D8 pointed out how *“It’s as if there’s space between these tissues. But it’s not. It’s vacuum sealed, and it’s just entirely different. That’s why the standard model cannot bring the whole picture.”*

[T2-C2] Lack of support for hands-on and real-world needling and palpation practices

Participants frequently discussed the concept of “*experience*” . We observed that the term held different meanings for different individuals. For experienced doctors, it mostly refers to treating patients with complex medical conditions. While for novice doctors, gaining experience by seeing a large number of patients was deemed most crucial. Even with guidance from supervisors, proper localization of target points through palpation and accurate needle depth requires experience, as each patient’s body and sensitivity to needling are unique. Although students have lab classes to practice on each other as operation subjects, this opportunity is not sufficient: *“The lab is great because you can palpate on your partner, but it’s only still one body, one body structure” [S9]*. To overcome this lack of practice, students usually ask their families and friends to act as operation subjects. S4 further confirmed the struggling experience of trying to learn from real bodies:

“When I practice on my big-muscles neighbor, it’s a totally different feel compared to my lab partner. Everybody’s anatomy is unique, and it can be challenging to feel the right tenderness and decide the right depth” [S4].

Such practice leads to insufficient feedback on whether the localization of the acupoints is correct, as previously discussed (see T1-C3 in Sect. 6.5.1). However, the stakes are higher at this stage, as inaccurate localization may result in harm to the patient.

[T2-C3] The limited view of what is happening beneath the skin creates safety concerns

While acupuncture is generally considered a safe procedure, it might also cause life-threatening accidents (169). For example, some acupoints, which are usually near important organs, nerves, or arteries, are referred to as dangerous or difficult acupoints. The names indicate that these points are challenging and potentially risky to needle if proper technique is not used. Some participants reported preferring alternatives for difficult points due to safety concerns, unless they're confident in the patient's anatomy. For example, D4 usually doesn't encourage his students to choose those points, *"unless you're an acupuncture master"*. As an experienced but humble doctor, he doesn't recognize himself as one of those masters. D3, a novice doctor, said he usually plays the safe card, probably because he lacks confidence. Both doctors kept stressing their safety concerns: *"Safety always comes first, and then comes effectiveness"* [D3].

Other participants stated that proficient practitioners should be well-trained in school and *"should be fearless of them [the difficult points]"* [D5]. When we referred to the difficult points as *"dangerous points"* while talking with doctor D7, he chuckled and corrected us: *"We could say they're 'difficult points.' Still, they're not actually 'dangerous.' Students are not very confident in clinics mostly because they don't highly understand the anatomy below the points"*. Being trained in the same institute, student S7 found it very important not to be afraid of any parts of the body. This is usually achieved by knowing the anatomy to a very high level.

As outlined in our literature review (Sect. 6.3), imaging technology has been recognized as effective way to enhance acupuncture safety (100; 105). After engaging with our cultural probe and reflecting on the power of visualization, almost all the participants agreed that visualizing what happens beneath the skin would address the difficult points issue and improve effectiveness and safety.

"We take four years to practice safe needling techniques, yet we still avoid them during real practice... Sometimes it's necessary to do that [needling difficult points], and then it becomes a problem. [At this point] I want to take things out and see what's underneath" [S2].

Like S2, students and novice doctors stated how better visualizations could help primarily to “understand how deep the needle is going” and “to make sure you’re not needling something, a nerve, or hitting something” [S9]. More experienced doctors raised also other reasons why visualization of the structure beneath the skin of specific patients could be a game changer. We summarize them below across (1) balancing effectiveness and safety, (2) emphasizing patients’ local anatomy, and (3) debriefing acupuncture sessions.

1. **Balancing effectiveness and safety** – As discussed above in T2-C2, practitioners with different levels of expertise can achieve different levels of effectiveness even with the same treatment plans. Supervisors usually observed that novices tend to needle shallower or find replacements on difficult points. D2 elaborated on this concept and how it relates to expertise and training:

“Students usually don’t feel confident about using a longer and thicker needle to stick deep enough for fear that it would cause injuries. But if the local lesion is deep, or the patient is not sensitive to needling, the treatment efficacy is insufficient in this way” [D2].

She believes that students will feel secure and confident in targeting points when they can visualize the structures beneath the skin, which will lead to more effective acupuncture.

2. **Emphasizing patients’ local anatomy** – As introduced above in the background section (Sect. 6.3), medical acupuncture now involves techniques that directly needle the local anatomy of the patient, which brings both opportunities and challenges for needling. As an example, D6 mentioned that there is a technique in musculoskeletal treatment in which the needles target a specific joint or area of musculoskeletal discomfort. “That’s when the patient’s medical imaging data should be vital” [D6]. Regardless of how a target point is identified, the disease and individual characteristics of each patient can add additional complexities to the local anatomy in acupuncture treatment. D7 made a specific example:

“Asthma patients use their muscles for breathing, which changes the

anatomy structures and makes the ‘difficult points’ even more difficult. So it’s very important to learn the accurate situation [for the particular patient]” [D7].

3. **Debriefing acupuncture sessions** – Additional visualization has the potential to be a unique method also to reflect on the acupuncture practice after the treatment session. We noticed how the idea of introducing any extra device during a treatment session was usually refused by the practitioners, given how it might add burdens for both themselves and the patients. However, most of our participants found that a great time to see patients’ bodies introspectively, besides before the treatment, is right after the treatment. D8 argued well the value of visualization as a debriefing tool:

“[After the treatment,] I would be able to relate what I’m sensing internally with a visual image. I would be able to inform and learn from those images to improve my needling technique because I would have feedback” [D8].

[T2-C4] Difficult matching between Western medicine diseases and TCM principles and practices

While TCM and Western medicine are distinct, they are often used in conjunction in China and the US. TCM doctors may collaborate with Western medical doctors to provide comprehensive care. Therefore, it is important for TCM doctors to match their practices with Western diagnoses and treatment plans for effective care.

Though this seems straightforward, in practice, it can be challenging especially for students and novice TCM doctors who lack experience with Western diagnostic criteria. Our findings in this context can be summarized around three main pain points: (1) TCM diagnoses lack objective standards, (2) it is difficult to distill effective objective and subjective information, and (3) it is challenging to make integrative treatment plans.

1. **TCM diagnoses lack objective standards** – Unlike EBM diagnoses, TCM diagnoses rely more on subjective judgments than objective measures, meaning that they rely on the practitioner’s observations and interpretations rather than on measurable data.

For example, pulse diagnosis (172) is one of the four major assessments, which involves a using fingertip pressure to feel a patient's pulse through the skin. Many participants admitted that even experienced doctors may struggle with pulse diagnosis. S3 commented on the potential risks of relying on the subjective diagnoses of TCM: *"It's hard to convince the patients to trust TCM. For certain patients, it's crucial to explain your decision-making process and show the treatment plans with evidence"*.

2. Difficulty distilling and communicating patient's objective and subjective information

– During the participant observation stage, we observed three treatments provided by residents under the supervision of their supervisors.

Generally, they first gather patients' symptoms, conditions, and medical history. Alongside, they examine tongues, take the pulse, and perform a physical examination to formalize treatment plans. Each diagnostic technique confirms and validates the diagnosis. Then they brief their supervisors on the patient's condition to ensure that the treatment plan is optimized, while the patients prepare and rest. This is usually a very concise communication, therefore *"we have to build [the skills of] how to present a case to a supervisor properly...however, we [the residents] may not get it well"* [S2]. Supervisors expressed similar concerns about students *"only asking patients' symptoms as a process but not actually extracting the crucial information for diagnosis"* [D7].

Besides, acupuncture treatment sessions often involve longer communication and more diagnostic information than common primary care visits. This can be both beneficial for learning about patients and challenging for highlighting crucial information. S8 recounts one particular episode:

"I'm listening to my patients and want to share all the same [with my supervisor]. But there are so many... My strategy now is to stick to their chief complaint and the supporting facts. What actions can relieve the symptoms immediately" [S8].

3. **The challenges to create integrative treatment plans** – Our interviews outlined how the integration of TCM and EBM methods can enhance learning. For example, as we discussed the difficulties mastering subjective TCM pulse diagnosis, S2 explained her strategy on *”[using] Western medical diagnosis to aid in understanding different pulse presentation”*.

More generally, experienced doctors agreed that for common diseases, incorporating Western medicine with Eastern diagnosis provides a valuable learning opportunity for students. They identified one major challenge in the integration of these two approaches, with Western medicine focusing on local anatomical stimulation (referred to as *”branch”*) while TCM emphasizes whole-body, systemic treatment based on TCM theory (referred to as *”root”*). They underlined that the most effective diagnosis and treatment plans integrate both root and branch methods in order to achieve optimal results. However, under such complex cases, D1 mentioned how *”diseases that are visible to the naked eye are actually quite easy to diagnose. But those that are interrelated and functional are more difficult. For example, a patient with lower back pain is likely not just a problem with the lumbar spine [...] it could be an issue with the digestive system, or it could be a problem with the kidneys”*.

[T2-C5] Expanding opportunities for medical images in acupuncture

Given the importance of patient anatomy in acupuncture treatments, doctors often recognize medical imaging as a critical dimension of data. In clinics, patients, especially those with orthopedic issues, usually bring their medical images to their acupuncture doctors. With these data and reports from the radiologists, *”their findings will help us tailor the treatments to be more specific”* [D7]. D8, for instance, recalled how her special training in medical imaging contributes to her acupuncture practice now:

”The way imaging contributes [...] it really helps me see the bone and connective tissue, the facet joints, nerves, and what’s going on to the disk space.” [D8]

For this reason, she emphasized the value of access to medical images of the same disease in different individuals during the training stage, stating that this is the “*golden thing*” they desire most. Similarly, D4 outlined that medical images are valuable resources for teaching students about pathology and objectively explaining treatment plans. He believes that the fastest way for a student to learn is through imitation and practical application. To this end, D4 envisions using a set of images from different patients with the same disease to demonstrate the difference in both EBM and TCM theories, and how he can tailor treatment accordingly.

Although acupuncture doctors recognize the value of patient medical images, our pre-screening questionnaire revealed that they are not being utilized as frequently as anticipated. We found that this is a common issue both in China and in the US, often due to a lack of equipment or insurance coverage. As a result, doctors in both countries tend to only refer patients for medical imaging when palpation diagnosis indicates a serious concern that may impact the decision for acupuncture treatment. D1 comments on this issue and outlines how, if it were possible, adding medical imaging to the current workflow would be ideal:

“My workplace does not have the necessary conditions for taking medical images. So if the patient has not had an imaging examination before, I usually will not require them to go to the hospital for an examination before treatment, unless it is particularly severe. I can diagnose from a physical examination. But for objectivity and also some legal requirements, it is still necessary to do so. If we have the equipment nearby, we will certainly do it. I am inclined towards this more clear and objective diagnosis. This is also much easier to be understood (by the patients)” [D1].

6.5.3 Demonstration and Collaboration

Demonstration and collaboration activities include explaining treatments and demonstrating the treatment results. In this section, we outline opportunities that arise from such collaborative activities in three common scenarios:

- A student working with their supervisors as observers, assistants, or practitioners in clinics.
- A doctor explaining the treatment to the patient and their families.

- A TCM doctor collaborating with Western doctors.

The themes below outline demonstration and collaboration activities, cutting across all three scenarios.

[T3-C1] Need for better supports to discuss treatment plans with supervisors

In the previous section, we outlined how presenting observations and treatment plans is challenging for residents (T2-C4). During those exchanges, we sometimes observed confusion and a breakdown of the communication, as was also confirmed by S6:

“I’m not always on the same page with my supervisor. When this situation happens [a disagreement], I usually follow their recommendations and think about it later.” [S6].

Reflecting on similar episodes, their supervisors also recalled that the most difficult part is helping students understand the reasoning behind choosing one acupoint over another, as students have difficulties understanding the basis of each selected point. S4 believes that using interactive visualization in VR could solve this problem:

“I can see it integrated so well if we had a tool like that [Virtual Reality]. Imagine we have a clinic group, and then in the centers where we meet with our supervisor, we have the visual to where we come out and talk, where you could show them the 3D imaging of the body. It can be used for [practical] technique-wise purposes, but also, maybe show what happens when I push over here and how it affects the other side of the body or something...” [S4].

Besides, student S6 wanted the application to further show different types and sizes of needles to help her decide which needle to use and how far different sizes of needles would have to go into the spine and muscles: *“our supervisors don’t usually talk about such information much” [S6].*

[T3-C2] Lack of tools to discuss integrated plans across EBM and TCM

As we mentioned above, more and more doctors realize the importance of collaborating across Western and Eastern approaches.

For example, as expressed by D6, it is beneficial for both TCM and EBM doctors to work together: *“We’re not at a point where it’s easy to request labs and imaging. Knowing how to*

network and talk to other professional practitioners, MDs, and physical therapists is a good practice. It helps build relationships, network, [submit] cross-referrals, and consult in difficult cases. It would be a win-win” [D6].

A good example of such collaboration is the rehabilitation clinic where D2 works: a significant part of her work in post-stroke rehabilitation is collaborative, as she described when talking about the rehabilitation assessment meeting they regularly hold for the incoming patients:

“Our assessment meeting includes rehabilitation therapists, rehabilitation physicians, rehabilitation nurses, traditional Chinese medicine practitioners, massage therapists, and physical therapists. The patient’s attending physician will lead the discussion, and each person will report from their own perspective, after which we will have a comprehensive discussion. As a TCM doctor, I need to explain the diagnostic principles, the acupoint selection criteria and reasons, herbs, and additional treatments such as massage to everyone. Helping the patient achieve the functional level they want to recover requires the work of the entire team and a holistic approach.” [D2].

While this meeting is highly collaborative, D2 believes that there is a need for better support to discuss patients’ data and understand the treatment plan. A similar example raised by D6 is post-surgery recovery, in which acupuncture has been demonstrated as an effective rehabilitation method: *“We need to better understand where and what is happening with the surgery, where the scar tissue might be, what channels are affected” [D6].*

Overall our participants stressed that an effective treatment plan should be based on understanding each other’s practice and *“Being able to work integratively will help patients recover better” [D7].* But currently, there is a lack of suitable tools to facilitate seamless collaboration and communication.

[T3-C3] Challenges of explaining treatments to patients and demonstrating results

New providers in the medical field often find it challenging to feel confident when interacting with their patients in clinical settings.

D3 mentioned that a significant challenge for him is the need for confidence: as a new doctor who has just begun working independently without the guidance of supervisors, he

lacks confidence in his abilities. Additionally, even when dealing with confident cases, he sometimes has hesitation about communicating with patients. To dive deeper into this barrier, when participants discussed their lack of confidence, we asked about their strategies for handling this situation. Many mentioned that being able to provide an intuitive illustration of their practice could help reduce uncertainty and build trust with patients. For example, S2 believes that her ability to intuitively present a TCM treatment plan in conjunction with the patient's EBM diagnosis instills trust. Also, from D2's experience, effectively demonstrating the progress made in the treatment so far is the most effective way to build reliance with patients and their families: *"It is best to provide data or image-based stimuli to the family members. For example, looking at an image and saying, 'Ah, one-third has healed, and two-thirds on the second time!' This kind of intuitive effect is easily recognized [...] if you use professional methods to explain the process and emphasize the effect, most people can accept it"* [D2].

D1 explained how a major barrier to introducing such visual support is that TCM treatment relies on patients' or practitioners' subjective feelings, which are *"not always reliable for building the whole picture"* [D1]. He further raised an example about some studies using tomography to visualize the effectiveness on the needling region, *"if I had such a device in clinics, I'd also use it for demonstration"*.

Based on the feedback and challenges reported by acupuncture doctors and students, it is clear that incorporating immersive visualization tools into their daily routines could have a significant impact. In the next section, we will explore the specific functionalities that should be designed to meet their needs.

6.6 Results and Discussion

In this section, we first summarize how the challenges raised by the participants are rooted in different acupuncture tasks. We then discuss how specific functionalities can be implemented to support participants' requirements for each task.

6.6.1 Major Tasks in Acupuncture Requiring Additional Support

Through our need-finding, we identified five major tasks, for both doctors and students, that need to be supported to overcome the challenges that they have reported (Sect. 6.5). To better outline the connection between the tasks, the themes, and the challenges outlined above, in the discussion below, we refer back to specific Themes with (T#) and Challenges with (T#-C#). Fig. 6.6 summarizes the five major tasks we identified and the challenges that they need to overcome from our findings.

(1) Comprehensive Cross-Referencing – The main task of the first 1-2 years of study is to learn the fundamental knowledge (T1) of both TCM and EBM. A Cross-Reference that provides a comprehensive overview of these two approaches to medicine, and helps students understand how to integrate them into their practice would be highly beneficial. As a tool to build theoretical foundations, it would cover a wide range of topics, including TCM acupoints and meridians (T1-C1), and the ability to associate TCM and EBM body theories (T1-C2). A Comprehensive Cross-Reference can also serve as a valuable reference for students to consult as they continue to learn and develop their skills as practitioners. If the cross-reference is augmented with individual body references, it can also provide guidance on how to apply this knowledge in clinical settings (T2-C1, T2-C3, and T3-C2).

(2) Diagnosis and Decision Making – Accumulating experience in diagnoses and decision-making is crucial for the professional development of TCM doctors. Despite having a solid theoretical foundation, residents and novice doctors may still encounter challenges in practice. This is because patients may present with different TCM constitutions for the same western disease (T2-C4), and a lack of experience in palpation and needling (T2-C2) can make it difficult to determine the details of treatment plans such as needle size, angle, and depth (T2-C3). Although we expect doctors to keep building their skills and knowledge throughout their careers, one effective way of supporting the development of diagnostic and decision-making skills is to expose them to a wide range of medical images, both during training and during clinical practice

Tasks	Challenges		
	[Fundamental] T1	[Experience] T2	[Cooperation] T3
Comprehensive Cross-Reference	C1, C2	C1, C3	C2
Diagnoses and Decision Making		C2, C3, C4, C5	
Needling	C1, C2, C3	C2, C3	
Assessment and Reflection	C3	C3	
Demonstration and Collaboration	C2, C3	C3, C4, C5	C1, C2, C3

Figure 6.6. The five major acupuncture-related tasks that need additional support, and the list of challenges that these need to overcome. The full description of each challenge can be seen in Fig. 6.5

(T2-C5).

(3) Needling – Due to safety considerations, entry-level students only have limited opportunities to needle human bodies. To properly prepare for needling patients soon, they must develop the ability to locate target points precisely and utilize the correct needling techniques (T1-C1, -C2, and -C3). This requires a professional level of understanding of local anatomy structures and simulation of the needling practice. After properly building their abilities on standard anatomy models, the next challenge will be adapting to different individuals while maintaining a balance between effectiveness and safety. This is especially important for complex cases where a patient’s previous therapy has affected local anatomy structures (T2-C2). In these situations, a full awareness of local anatomy structures is crucial to ensure effective and safe treatments (T2-C3).

(4) Assessment and Reflection – Immediate assessment and feedback on the practice are crucial yet difficult to achieve in acupuncture training due to the subjective nature of the assessment process. While hands-on training and feedback can help students learn to apply their theoretical knowledge in a practical setting and receive immediate feedback on their progress, objectively assessing the correctness of their techniques is difficult. Often, students can only practice their techniques with the guidance and supervision of their instructors, which may not fully reflect the real-world situations they will encounter as practitioners (T1-C3). To overcome these challenges, acupuncture students need access to various assessment tools and methods

that can accurately and efficiently evaluate their skills and knowledge. By actively seeking out opportunities for assessment and feedback, acupuncture students can continually improve their skills and confidence as practitioners (T2-C3).

(5) Demonstration and Collaboration – Effective collaboration between doctors and students requires clear and efficient communication. To support such collaboration tasks, especially for entry-level students, the clinical practice should include ways of helping novices to fully understand the TCM and EBM principles and techniques (T1-C2) and assessing their performance (T1-C3). It is essential to guide students on making acupuncture plans for individual patients based on their medical materials because this allows them to accurately identify and target specific areas of concern. Medical imaging, such as MRI or CT scans, can provide detailed information about a patient's anatomy and physiological processes, which can be invaluable in the planning and execution of acupuncture treatment. Lacking such resources slows the students' progress in analyzing and interpreting medical data (T2-C5), matching an EBM disease with a TCM diagnosis (T2-C4), and their abilities to tailor the treatments for individuals (T2-C3). Due to the differences between TCM and EBM training and overall philosophy, TCM doctors tend to be weaker in interpreting EBM materials, while EBM doctors have problems understanding TCM principles. TCM doctors often rely on a holistic approach to treatment, while EBM doctors tend to focus on interventions based on scientific evidence, and this can lead to differing perspectives on patient care. Clinicians lack an effective method to create a common ground between the two practices from both theoretical and technical perspectives (T3-C1, -C2, and -C3).

6.6.2 Design Opportunities of VR-based Acupuncture

Based on our analysis of the tasks and challenges, we have identified two potential strategies that can cater to the needs of all three levels of expertise among our target users (Early-stage Students, Residents and Novice Doctors, and Experienced Doctors). Fig. 6.7 depicts the features of these two design strategies, outlining how they support the above-defined tasks (and hence overcome the challenges), and what level of expertise they support. Since our investigation

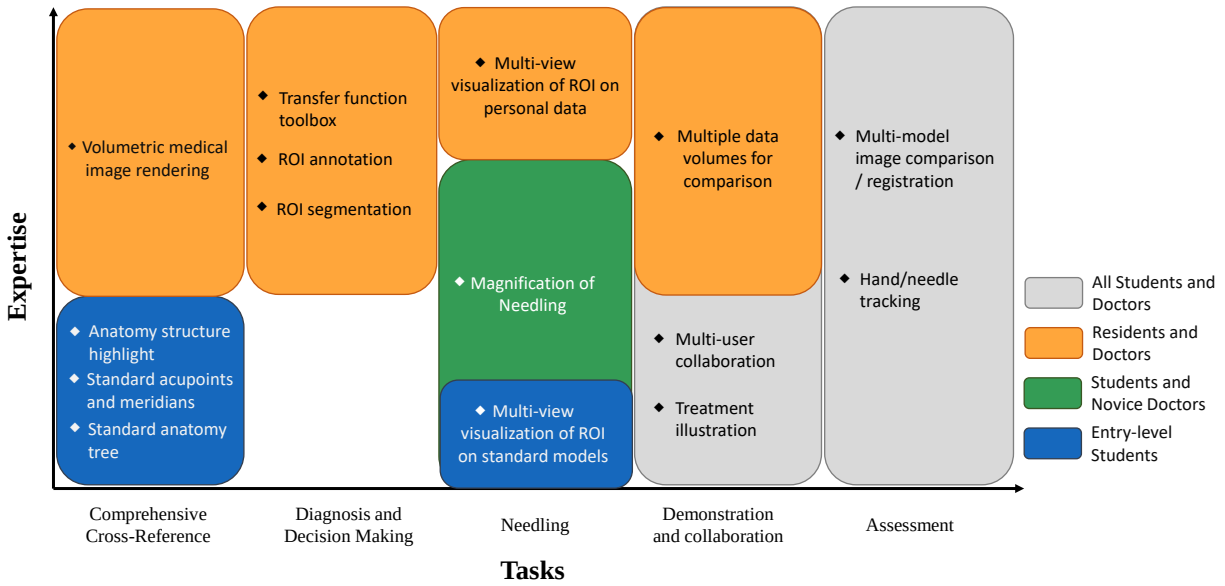


Figure 6.7. Technology features in five tasks for different levels of expertise acupuncture students and doctors to address their challenges.

was rooted in opportunities for immersive visualizations in Virtual Reality, we show how VR is the optimal strategy to implement both design strategies and their specific features. The two strategies can be implemented in a single VR application or across two VR applications, and users can choose the one that best suits their current needs.

Design Considerations for the Integration of Standard Human Anatomy Features

As introduced in the related work, existing VR training systems for acupuncture visualize standard 3D human anatomy models marked with acupoints and meridians and already demonstrated effectiveness in existing research. In this section, we outline how tools that are used in these settings should be designed and extended to support the task outlined above and overcome the challenges reported by our participants.

Given the importance of learning as precisely as possible the acupoints' and the meridians' location from TCM, and the correspondence with human anatomy from EBM, systems and visualizations should be able to support early-stage students guided by their supervisors. We identified the following features as core functionalities in this design:

- **Visualization**

- Found on a detailed atlas of the anatomy of every single organ system.
- Overlay meridians and acupoints against human anatomical systems of the body.
- Highlight a meridian and show the flows.
- Provide an information panel to illustrate detailed information for each acupoint.

- **Needling Simulation**

- Simulate needles of different types and sizes.
- Show an adjustable magnified view of the intersecting point with selected local anatomical components.
- Provide optional needling targets and assess the correctness of the current practice.
- Illustrate potential effects around the needling region.

- **Collaboration**

- Allow multiple users to view and interact in the same virtual environment.
- Enable different levels of permissions for supervisors and trainees.

Combining these core functionalities will allow for the creation of immersive 3D visualizations that bridge the gap between 2D textbook information and 3D human anatomy through 3D rendering (T1-C1). Overlaying acupoints and meridians will directly outline the relationship with the local anatomical structures instead of showing information floating over the surface skin (T1-C2). Fig. 6.8, illustrates a simple prototype showing how these features could be integrated in the trainee's view when working with a supervisor inside a virtual training environment.

As a training application, besides providing a basic magnified view from the needling position as in most existing systems, the core features above will provide ways for trainees to mimic and evaluate their choice of needles, needling angles, depth, and manipulations (T1-C3). For example, the acupoint ST2, which is situated close to the optic nerve and requires very high

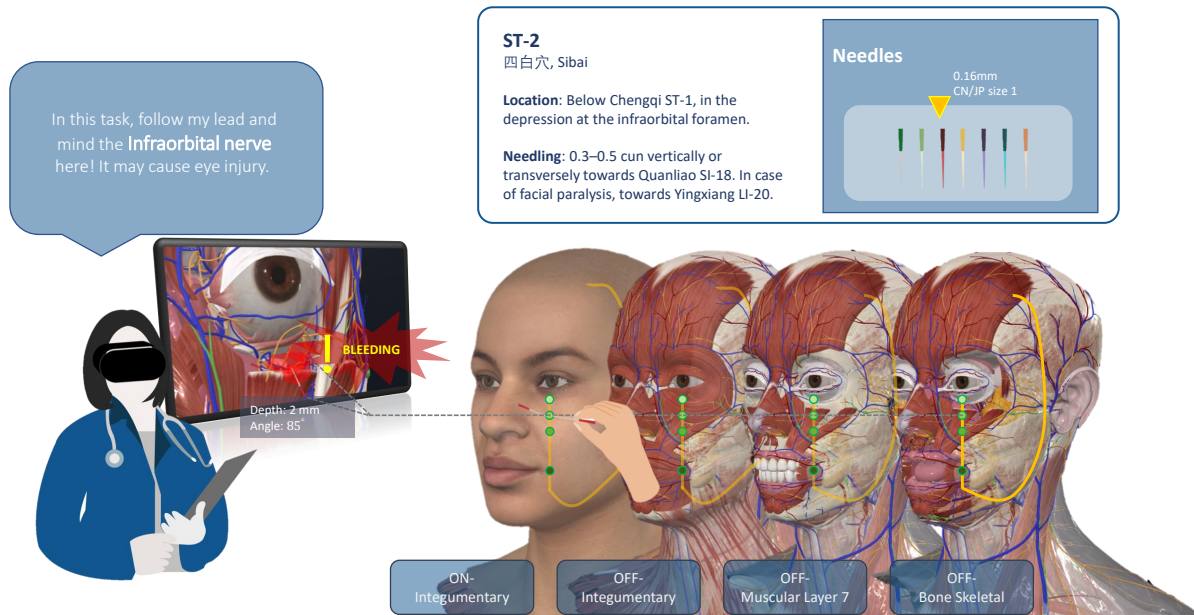


Figure 6.8. Design illustration for the Integration of Standard Human Anatomy. A trainee’s view of needling acupoint ST2 on a standard human anatomy model guided by a supervisor inside the virtual training environment (Standard anatomy model images are captured from Elsevier’s Complete Anatomy 2023 (40), Windows version).

localization precision, is arduous to assess from the outside skin (T2-C3). As shown in Fig. 6.8, an effective assessment tool would help with the localization, but also show the consequences of mistakes, like if the needle goes through a capillary, the body starts to bleed. Finally, in order to facilitate collaboration, an efficient training system will not only support multi-user functionality but also implement a flexible permission system that accommodates the varying roles and responsibilities of users. For instance, as demonstrated in Fig. 6.8, a supervisor should be able to assign and monitor tasks, while a trainee should be able to access and complete them. This will ensure that the users in different roles can work together effectively (T3-C1).

Design Considerations for the Integration of Medical Imaging

As discussed above, training systems that only focus on standard human anatomy models are most effective in addressing the challenges of learning fundamental knowledge (T1). However, while standard models may be useful in certain contexts, they are inadequate for senior students to acquire clinical experience (T2) or for doctors to use in their clinical practice and communication

(T3). To the best of our knowledge, few acupuncture training systems are based on visualization and manipulation of medical images.

Medical imaging techniques can include CT and MRI scans for preoperative procedures, and ultrasound or fMRI for intraoperative purposes. These techniques provide valuable information and insights that can help novice acupuncture doctors to gain clinical experience and to improve their diagnostic and treatment skills. Compared to a standard-model-based of training, based on our need-finding, a medical imaging-based planning and training system should provide the following functionality:

- **Visualization**

- Show high-resolution volumetric visualization from specific 3D medical images.
- Integrate a library of existing medical images from a public database.
- Visualize target needling points against human anatomical systems of the body.
- Provide the ability to observe the target regions of interest (ROI) with cross-section and 3D selection views.
- Introduce multiple data enhancement tools to pull out ROI.
- Enable automatic anatomical structure (e.g., organ, muscle, and nerve) segmentation and multi-modality image registration.

- **Needling Simulation**

- Include all the needling simulation features as described for the standard-model-based one.

- **Collaboration**

- Include all the needling simulation features as described for the standard-model-based one.

disease will help to visually demonstrate the impact of the disease on the body and potentially allow also patients to see what the clinician is thinking and alleviate a lot of their fears (T3-C1). During actual treatments in the clinic, when patients bring their own digital images, the clearer and more effective viewing of patients' body will enhance the objectivity of treatment decisions (T2-C4). Also, a complete understanding of the patient's situation inside their body will allow doctors to avoid potential scar tissue during the procedures (T2-C3). Additional functionalities like anatomical structure segmentation can also be introduced to help addressing the limited number of TCM doctors proficient in interpreting medical images, to manage the significant demand for assistance with identifying and segmenting ROIs, and to help localize the needling and explain some of the patients' pains through additional information for muscle and nerve segments.

Overall, an intuitive visualization system based on medical images would enhance communication between students-supervisors, patient-doctors, and TCM-EBM doctors. While EBM doctors widely accept medical imaging-based visualization systems for diagnosis, monitoring, and surgical planning, it could become a great starting point for TCM and EBM doctors to work together and bridge the gap between western and eastern medicine (T2-C4, T3-C1, and T3-C2). Repeated imaging pre- and post-treatment will allow a better discussion of the effects of acupuncture and will be essential to adjust the plans for the next step (T3-C3).

6.6.3 Limitations

In our study, we recognize that the level of experience with VR technology can impact participants' perceptions of its usefulness and potential applications. We acknowledge that only a small percentage of our participants had significant experience with VR, which may have limited the depth of their feedback on the technology. In future studies, we plan to address this limitation by providing more opportunities for participants to become accustomed to working in VR to ensure that they can provide more informed feedback on the technology.

6.7 Conclusion and Future Work

This chapter presents a need-finding analysis focused on investigating the potential introduction of immersive visualizations in VR to empower medical acupuncture doctors and students. Our 17 participants shared their experiences with learning, practicing, educating, and collaborating in their daily routines and discussed their challenges and design opportunities in these activities. We outlined those challenges at three different levels of expertise and identified three guiding themes: Learning fundamental knowledge, accumulating clinical experience, and demonstration and collaboration.

As the need for integrating the treatment rooted in traditional practice with modern technologies increases, it is important to identify the starting point to leverage medical imaging in acupuncture treatment. By reporting 11 barriers, we unveiled key opportunities for designing effective VR systems, and describe them in terms of their relationship to five specific tasks: comprehensive cross-reference, diagnosis and decision-making, needling, assessment and reflection, and effective collaboration, including interaction across TCM and EBM. We showed how two specific design strategies rooted in the visualization of standard human anatomy and medical imaging can empower acupuncture practitioners in their daily routine through state-of-art VR visualization and interaction technologies.

Our next goal is to develop a prototype of a collaborative virtual reality system using medical imaging visualization, to address the challenges faced by residents and novice doctors in gaining practical experience. We anticipate that our research so far, and the presented work will be beneficial for researchers in the future who are working on developing 3D visualization-based applications in the field of acupuncture and integrating them into existing systems.

6.8 Acknowledgments

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Nadir Weibel. The dissertation author was the primary investigator and author of this paper.

Chapter 7

AcuVR: a Personalized Medical Imaging-Based Virtual Reality Acupuncture Training System

7.1 abstract

Acupuncture is a form of medicine that involves inserting needles into targeted areas of the body. While contemporary acupuncture education strives for greater accuracy, safety, and evidence-based practice, current approaches are limited in their ability to provide immersive and realistic training experiences. Virtual reality (VR) technology has emerged as a promising tool for enhancing medical training, providing realistic and immersive experiences to improve skill acquisition. This paper presents a rigorous and iterative design and prototyping process for developing AcuVR: a VR Acupuncture Training System that leverages medical imaging to deliver unparalleled anatomical accuracy and fidelity. Through the integration of MRI/CT data in the form of DICOM images, AcuVR offers a realistic, individual-based experience, enabling practitioners to refine their skills in a safe and controlled setting. The iterative design approach employed in this study facilitated continuous refinement and optimization of AcuVR. Multiple cycles of feedback from acupuncture experts, medical educators, and trainees were used to fine-tune the system's usability, functionality, and educational effectiveness. Through an exploratory study involving eight acupuncture professionals, we conducted an evaluation of the

AcuVR system. The results of this study revealed a remarkable 100% overall satisfaction rate among the participants. These findings provide strong evidence of the effectiveness and potential of AcuVR as a valuable component in acupuncture training programs. The positive feedback received from the participants demonstrates the promising impact and significance of AcuVR in enhancing acupuncture education and practice.

7.2 Introduction

Acupuncture (77) is a highly regarded therapeutic practice, known for its effectiveness in providing targeted relief through the precise insertion of thin needles into specific areas of the body. It has long been used in clinical practices in both Eastern and Western societies. As the demand for acupuncture services continues to grow, contemporary acupuncture education endeavors to prioritize accuracy, safety, and evidence-based practice. However, compared to general medicine training, current acupuncture training methods often face challenges in accessing adequate resources and incorporating the latest technological advancements necessary for comprehensive education.

Virtual reality (VR) technology has emerged as a promising solution for enhancing medical training across numerous specialties. It provides practitioners with opportunities to refine their skills in a controlled and safe setting, mitigating risks associated with traditional training methods. VR has proven successful in various medical training domains, such as surgery, anatomy education, and patient interaction simulations. Comparably, there is a notable gap in the development of training systems designed for acupuncture. Moreover, the role of VR in the acupuncture training process requires further in-depth investigation and understanding.

In this paper, we present AcuVR, an acupuncture training system that leverages the power of virtual reality in addressing the limitations of traditional acupuncture training methods. AcuVR adopts an iterative design and prototyping process to ensure continual refinement and optimization of the system. The primary objective is to provide acupuncture practitioners with a

realistic and immersive training experience that enhances their anatomical accuracy, needling techniques, and patient interaction skills.

A key aspect of AcuVR is the integration of both DICOM (Digital Imaging and Communications in Medicine) imaging data obtained from MRI/CT scans and standard human anatomy models. Using DICOM images ensures anatomical accuracy and fidelity, enabling trainees to comprehend individual anatomical variations. By visualizing and interacting with authentic human anatomical structures, practitioners can develop a deeper understanding of the intricate relationships between anatomical landmarks and acupuncture points. Meanwhile, the inclusion of the standard anatomy model provides trainees with a tangible and accessible reference, facilitating ease of use, compatibility with traditional training methods, and enhancing their overall understanding of anatomical structures. AcuVR further enhances the training experience by linking and comparing the volumetric data from DICOM images with the standard anatomy model. This approach offers trainees a comprehensive training experience that enhances their understanding and skills in acupuncture practice.

To ensure the effectiveness and usability of AcuVR, an iterative design approach was employed, incorporating valuable feedback from acupuncture experts, medical educators, and trainees. Their input played a crucial role in refining various aspects of the system, including its functionality, educational effectiveness, and user experience. Through careful analysis and refinement cycles guided by their feedback, AcuVR has demonstrated promising potential in addressing challenges encountered in complex acupuncture education, such as enhancing anatomical understanding and improving needling techniques.

In summary, the contributions of this work are as follows:

- We use an iterative approach to design and prototype a novel VR acupuncture training system that addresses the limitations of traditional acupuncture training approaches.
- We evaluated the prototype with acupuncture professionals by conducting a pilot user study and semi-structured interviews to assess the desirability and feasibility of our prototype.

7.3 Related Work

7.3.1 Acupuncture Training

Contemporary acupuncture education programs worldwide integrate both classical theory and modern biomedical sciences (192). These programs emphasize the importance of understanding human anatomy, physiology, and pathology, enabling students to work with other healthcare professionals (174). Although acupuncture is generally considered a safe practice, studies showed that it can lead to various types of adverse events (AE), including organ or tissue injuries, infections, local reactions, and complications such as dizziness or syncope (25). To ensure effective and safe treatments, expertise in Evidence-Based Medicine (EBM) is essential, as it integrates the best available scientific evidence with clinical expertise and patient values. In EBM education, cadaver-based approaches have long been recognized for their valuable contributions in providing insights into the shape, feel, and function of the human body (17). Moreover, studies have demonstrated that medical imaging of cadavers not only enhances students' comprehension of human anatomy but also improves their understanding of the relationship between acupuncture needles and anatomical structures. Works focusing on X-rays (97; 84), CT scans (119), and Ultrasound (96) have reported remarkable benefits, emphasizing the significance of medical imaging in acupuncture education. Another popular training tool in acupuncture education is the phantom acupoints model (69), which has demonstrated effectiveness in improving needle depth accuracy. However, these models have certain limitations. One notable drawback is the lack of visual feedback for evaluation during needle insertion (95). Visual cues are essential for students to observe and assess the accuracy of their technique. Additionally, the models often do not provide corresponding data feedback (95), hindering students' ability to analyze and track their progress over time. Incorporating visual feedback mechanisms and data feedback capabilities into acupuncture training tools would enhance the educational experience, allowing students to refine their skills more effectively and objectively evaluate their performance.

7.3.2 Virtual Reality in Medical Education

The affordability of VR technology has sparked its widespread adoption across various educational settings, revolutionizing the learning experience by providing immersive and interactive opportunities (9). Extensive research consistently highlights the positive outcomes of VR-based education. Notably, VR enables enhanced performance and engagement, facilitating a more comprehensive understanding among learners compared to the traditional methods (87; 135).

In the medical education field, studies have shown that VR training outperforms traditional methods of learning anatomy, procedural skills, surgical procedures, communication skills, and clinical decision-making (161; 99). For example, an early comparative study involving 57 students investigated the educational effectiveness of a computer-generated 3D model depicting the middle and inner ear, resulting in impressive 18% improvements (121). In a more recent study, the use of VR training was found to enhance cadaveric temporal bone dissection performance by an impressive 35% when compared to traditional teaching methods (191). As VR enables simulation-based medical training that offers a safe experience for trainees to perform deliberate practice, it has increasingly been embraced in the realm of patient-based procedures (56; 145). This includes applications in dental and bone surgery (15), minimally invasive surgery (55), and endoscopy training (80), where the use of virtual reality technology has gained acceptance.

In terms of acupuncture training, traditional acupuncture training often relies on two-dimensional models, pictures, or auxiliary teaching aids to demonstrate the position of acupoints. This approach lacks details, intuitiveness, and accuracy, introducing significant cognitive load in the learning process (54). To address these challenges, researchers combined medical anatomy education in VR and acupuncture knowledge to create a virtual three-dimensional space for teaching acupuncture (28). This allows beginners to visualize the anatomical structure of acupoints, realistically simulate the acupuncture process, and provide a safe foundation to enhance clinical efficacy. For example, a teaching experiment at the Guangzhou University of Traditional Chinese Medicine utilized a virtual acupuncture teaching system to display meridian

outlines and anatomical details of key acupoints (138). One notable company that focuses on making VR solutions for general medical training experience is MAI (108). In 2021, their AcuMap (107) was the first commercialized acupuncture VR training system that incorporates anatomy, meridians, and acupoints on the standard 3D human model. Another trend in VR acupuncture research enables novice practitioners to localize acupoints on individuals with technologies including gesture recognition (188), face alignment (185; 187), and full-body tracking (39) to adapt to anatomical variations.

7.3.3 Integration of Medical Imaging in VR

Medical imaging plays a critical role in modern healthcare in both educational and non-educational contexts. It enables visualization and diagnosis of internal structures and conditions. Techniques such as computed tomography (CT) and magnetic resonance imaging (MRI) produce detailed cross-sectional images of the body, aiding in the detection and characterization of diseases. These imaging modalities often generate data in the Digital Imaging and Communications in Medicine (DICOM) format, a widely used standard for storing, sharing, and exchanging medical images and related information among healthcare professionals and systems.

Advanced visualization of medical imaging has become a significant area of research. The prevalence of 2D screens in DICOM viewers facilitates easy viewing of medical images. However, this approach poses challenges for clinical practitioners and students in extracting crucial 3D information, including anatomical structures, regions of interest, and spatial relationships. Today, there are many advanced DICOM viewer systems available that offer 3D volumetric visualization. These systems provide users with a more comprehensive view of imaging data, and they can be accessed on both desktop (157; 129) and mobile platforms (127; 132).

VR takes medical imaging visualization to the next level by creating immersive and interactive experiences. By integrating VR into medical imaging education, students can explore realistic complex or subtle anatomy (111) and engage in hands-on training simulations. While non-educational virtual reality in particular is being increasingly used for two main scenarios:

highly realistic simulators and highly interactive medical data visualization stations (130). A wide range of VR solutions already exist, integrating medical imaging with VR head-mounted displays. These solutions serve various purposes, including the general visualization of patient-specific 3D data volumes and models (140; 182; 154). Additionally, there are specialized applications designed specifically for surgical planning (159), simulation training (141; 56), and radiation oncology (67; 27), offering enhanced visualization and training experiences.

Medical imaging not only aids in accurate localization of acupoints but also helps in understanding the mechanisms of acupuncture and its effects on the body (49). By incorporating medical imaging into acupuncture research and practice, researchers and practitioners can visualize and study the intricate relationships between acupoints, nerves, blood vessels, and other anatomical features (83; 81; 82). This integration promotes a more rigorous and scientific approach to acupuncture, strengthening its position as a viable therapeutic option within evidence-based medicine. For example, recent research in Harvard Medical School integrates meta-analysis, resting-state functional connectivity, and diffusion tensor imaging (DTI) to identify potential locations of scalp acupuncture for treatment of dementia (23).

However, while medical imaging provides anatomical insights and VR offers immersive and interactive experiences, their integration specifically within the context of acupuncture has not been explored or established. To the best of our knowledge, our AcuVR represents the pioneering medical imaging-based VR application specifically designed for the acupuncture process. This paper presents a comprehensive exploration of the design, aimed at assisting acupuncture students in enhancing their comprehension, reducing mental load, and improving their accuracy in needle placement. By leveraging this innovative approach, students can gain a deeper understanding of acupuncture techniques and develop essential skills with increased precision and confidence.



Figure 7.1. Settings of (a) design iteration and (b) validation iteration.

7.4 Iterative Design

To improve the usability, functionality, and applicability of the system, we used an autobiographical approach and user-centered design, to gather feedback from three experienced doctors specializing in acupuncture. In this process, participants are actively involved in different iterations of the system's development to provide valuable insights and feedback based on their expertise and experience in acupuncture practice.

7.4.1 Participants

We enlisted a group of 22 domain-expert participants in the iterative design process. The participants consisted of 11 doctors and 11 students.

7.4.2 Procedure

Our preliminary design consisted of three design iterations and two validation iterations. Each design session lasted 45 - 90 minutes while each validation takes 15 - 20 minutes. The first design iteration was rooted in our initial needs-finding process, 17 participants took part; followed by the initial prototype evaluation in the second iteration, with one doctor (ID1) and two researchers (IR1 and IR2); and the enhanced prototype evaluation with two doctors (ID2 and ID3). The validation iterations are done with two advanced or clinical internship students (IS1 and IS2).

[I1]Iteration 1 - In the previous needs-finding process, We conducted 17 semi-structured interviews with participants nine doctors and eight students. We first explained basic VR concepts by showing volumetric medical imaging rendering-based VR applications to get them familiar with the context. We focused on two guiding questions:

- How could VR benefit your acupuncture practice?
- What are the possible features/information that might be particularly useful?

[I2]Iteration 2 - We developed the initial prototype using Unity3D and Oculus Quest Pro, based on [I1]. The prototype included essential functionalities such as a volumetric rendering setup, a transfer function toolbox, slicing planes, cross-section planes, and a magnification view of needles. One doctor and two designers were involved in the evaluation process. We began by providing a 20-minute demonstration of each functionality, along with a refresher on basic VR interaction techniques. Following that, participants were given 20-30 minutes to freely explore the system using the Thinking Aloud method. Finally, we discuss with them individually to identify missing features and gather feedback on potential improvements.

[I3]Iteration 3 - After incorporating the findings from [I2], we refined the system and invited two doctors to evaluate the improved version. The evaluation process followed a similar approach to I2. The goal of this iteration (I3) was to finalize the system details, assess the feasibility of the provisional design, and identify any setbacks or limitations that needed to be addressed.

[I4]Validation Iteration - After completing the implementation of the prototype, we invited two students to validate our system. Their role was crucial in assessing the functionality and performance of the system, ensuring its usability and stability for the study. By engaging students in the validation process, we were able to gather valuable feedback and ensure that our system met the user requirements and expectations. Their inputs and suggestions helped us identify potential technical issues in deployment and suggested appropriate settings for users to try in the upcoming study.

Iteration	Participants	Feedback		Design Changes	
[I1]- Initial Needs-Finding	Eight doctors and Nine students	F1	3D visualization of medical structures could benefit students by enhancing comprehension and improving training efficiency.	D1	Designed the initial prototype of the volumetric medical-imaging visualization-based VR system, which included a basic transfer function toolbox, cross-section plane, and a magnification view of needles.
		F2	Both standard anatomy models and individual volumetric medical imaging are beneficial, but target different levels of students.		
[I2]- Initial Prototype Evaluation	One doctor with two designers	F3	Having too many different 3D user interaction methods could be overwhelming for users who are not familiar with VR.	D2	Remove redundant interaction methods and retain only bare-hand interaction.
		F4	The interaction for holding and manipulating the needle should aim to replicate the most natural way based on real-world practice.	D3	(i) Refine the holding gesture regarding real practice. (ii) Improve ease of use for needle selection and manipulation (iii) Set the needle to stick on the target volume once it's released by the user.
		F5	Linking a standard anatomy model to the target virtual data volume for comparison, and overlaying acupoints and microsystem with anatomy, would enhance the learning experience.		D4
		F6	Presenting anatomy structure information in a contextually relevant manner could improve the effectiveness of the training.	D5	Add the standard model-data volume linkage feature for registering a standard model onto the data volume.
[I3]- Enhanced Prototype Evaluation	Two doctors with one designer	F7	Improve needle visualization inside the data volume to provide better visibility of the needle's path and target.	D6	Display guided information with the ability to enable/disable each layer of information.
		F8	Streamline the user interface by reducing the number of components around the single volume to enhance usability and user experience.	D7	Enhance the needle rendering and render the needle onto slicing planes. Make the 3D UI interfaces uniform and add enable/disable interfaces, as well as instance identifications.

Figure 7.2. Feedback insights and design changes from preliminary interviews and iterative design.

7.4.3 Findings

Figure 7.2 shows key takeaways from each iteration, including the experts' general attitude towards this system and their suggestions on functionalities, interactions, and interface design.

Our interview with the domain experts during the first iteration confirmed the validity of almost all the major design ideas we presented. It uncovered insights that led us to identify five key components, which we will discuss in detail in the upcoming section (Sec. 7.5). The two subsequent iterations further polished the details, ensuring the effectiveness and user experience of the training system. Through the iterative design process, we gained two crucial lessons that served as vital guiding principles for all our design considerations.

Leveraging Layered 3D Standard Models and Individual Data Volumes for Acupuncture Training -

Both 3D standard anatomy models and individual medical imaging scans are valuable resources for acupuncture training. Participants recognize the former is suitable for entry-level students to

grasp basic concepts, while the latter is beneficial for higher-level education with complex points and techniques and also real practice on individual patients in clinics. “ *If there is a radiologist report, their findings will help us tailor the treatments to be more specific.* ” [ID7]. However, it is crucial to consider that students/practitioners with limited expertise in radiology may struggle with interpreting medical images themselves. “ *I always ask to see their records...but I don’t diagnose from the images.*” [ID8].

Therefore, we recognized the value of incorporating a layered standard 3D model that provides a comprehensive representation of the human anatomy, allowing for a detailed examination of specific anatomical features. Combining this layered model with individual data volumes empowers practitioners to explore and visualize the interplay of various anatomical structures, facilitating analysis of patient-specific variations and anomalies.

“The way [medical] imaging contributes as it really helps me see on a bone and connective tissue, the nerve passing through the foramen. Those information can not be extracted from the standard model, because individual’s structure could be very different and pathology can change the appearance” [ID7].

This integration leverages extensive anatomical knowledge for gaining insights into patient-specific structures within the data volumes.

3D Interaction Modalities in VR –

We observed that many participants lacked prior experience with VR during the initial stages [I1]. Participants in the [I2] took up to 15 minutes to become comfortable with using controllers for interacting with the user interface and objects in VR. Switching between different interaction modalities proved to be more challenging. As a result, we made the 3D interactions consistent with bare hands or controller hands after [I2]. Notably, participants demonstrated improved performance and preference when using bare hands, particularly during needling simulations, as it closely mimicked real-world scenarios. “ *I was amazed by how I can see and use my hands in VR. It feels so much more natural.*” [ID10]. Also, some users preferred using controller hands due to smoother and more precise tracking, while still maintaining intuitive operations.

7.5 System Design

The system prototype is developed using Unity3D in combination with Oculus Quest2 to leverage advanced hand-tracking capabilities. It is optimized to run via Oculus AirLink to guarantee high-quality volumetric rendering and smooth performance, allowing it to be synced seamlessly between the desktop and the headset for an immersive experience.

Based on the literature review, it suggests that software rooted in medical imaging visualization typically shares some essential features. These features can be summarized as follows:

- **Volumetric rendering:** This feature involves converting volumetric data into visual representations by assigning color and opacity to each voxel based on its properties.
- **Parameter adjustment:** This feature allows users to adjust various parameters to emphasize specific features of interest within the data volume.
- **Cutting plane:** This feature enables the extraction of a 2D plane from the 3D data volume, which can be further analyzed internally.

Building upon these findings and following an iterative design process, we have tailored these features to meet the specific needs of acupuncture training. We have enriched the parameter adjustment functionality to incorporate a workflow of a set of transfer functions. Additionally, we have expanded the cutting plane feature to include two types of slicing planes: cut-out planes and view planes. Furthermore, we have introduced two new essential components to the software:

- **Needling Simulation:** This component allows users to simulate their needling practice as if they were in real scenarios, providing a realistic training experience.
- **Standard Model Registration:** This component facilitates the registration of a standard anatomy model to an individual's data volume. It enables side-by-side comparison, assisting in the process of needling by providing a reference point.

In this section, we elaborate on the implementation of the five major components, highlighting how AcuVR has been specifically tailored to meet the requirements of acupuncture training.

7.5.1 Volumetric Rendering

We incorporate three volume rendering methods: direct volume rendering (DVR), Maximum Intensity Projection (MIP), and Iso-Surface Volume Rendering (Iso-surface) for different visualization purposes.

Direct Volume Rendering- DVR method maps data volume intensity to visual attributes like color and opacity. The final color ($C(\mathbf{r})$) comes from integrating the volume rendering equation along each viewing ray, taking into account the data values ($\rho(\mathbf{r})$), transfer functions ($T(\mathbf{r})$), and lighting conditions ($L(\mathbf{r})$):

$$C(\mathbf{r}) = \int_{\mathbf{r}_0}^{\mathbf{r}_f} T(\mathbf{r}) \cdot \rho(\mathbf{r}) \cdot L(\mathbf{r}) d\mathbf{r} \quad (7.1)$$

By fine-tuning the transfer function and lighting parameters, it unveils different regions of interest.

Maximum Intensity Projection: MIP method selects the maximum intensity encountered along each ray, instead of accumulating the values. The core equation for MIP is:

$$C_{\text{MIP}} = \max(C_1, C_2, \dots, C_n) \quad (7.2)$$

It enables the visualization of structures with high contrast and enhances high-intensity features.

Iso-Surface Volume Rendering: Iso-surface method extracts a specific threshold range

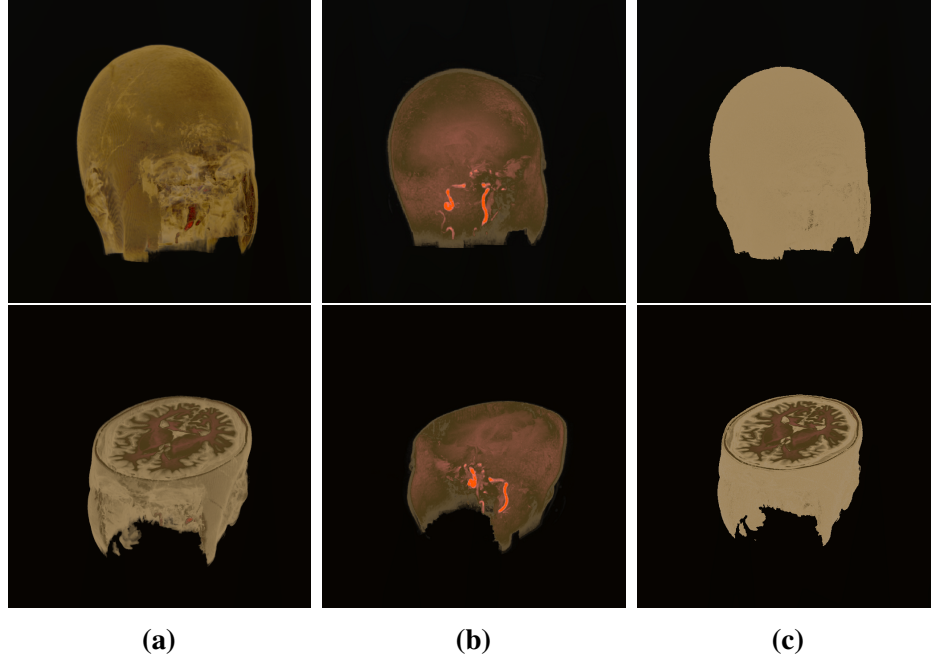


Figure 7.3. A head MRI data volume: whole (top) and cross-sectional (bottom) visualization using (a) Direct Volume Rendering, (b) Maximum Intensity Projection, and (c) Iso-Surface Volume Rendering.

and renders the corresponding surface:

$$f(\mathbf{r}) = \begin{cases} 1, & \text{if } \rho(\mathbf{r}) > \text{threshold} \\ 0, & \text{otherwise} \end{cases} \quad (7.3)$$

It creates a clear boundary and contours for better understanding and analysis of specific anatomical structures. Fig. 7.3 compares a data volume with three rendering methods.

7.5.2 Transfer Function

We drew inspiration from the work of Chourasia et al. (32), Lavik (92), and Zhang et al. (186) to develop effective intensity transfer functions for high dynamic range scalar volume data. Our approach incorporates three key components:

Contrast Enhancement-Firstly, given a pair of contrast limits (C_{min}, C_{max}) , the value of

each voxel C_x could either be cut off:

$$C_{x'} = \begin{cases} C_x, & \text{if } C_{min} \leq C_x \leq C_{max} \\ 0, & \text{otherwise} \end{cases} \quad (7.4)$$

or redistributed to enhance with a brightness factor C_b :

$$C_{x'} = (C_x - C_{min}) / (C_{max} - C_{min}) + C_b, \quad (7.5)$$

$$(C_{min} \leq C_x \leq C_{max})$$

Linear Opacity and Color Mapping-We utilize the intensity of the volume data to determine both its opacity and color, drawing inspiration from Lavik's work (92), as depicted in Fig. 7.4. The x-axis represents the density, while the y-axis signifies the corresponding opacity value. The underlying histogram aids in identifying the desired range for visualization, enabling users to add and adjust color and opacity handlers to refine the mapping. These interactions form a lookup table, allowing each intensity value to be mapped to a specific opacity and color value:

Listing 7.1. Opacity and color transfer function mapping

```
float intensity = ContrastEnhancement(currentPos);
src, opacity = LookUpTable(intensity);
color.rgb = src * opacity + color.rgb * (1.0 - opacity)
color.a = opacity + (1.0 - opacity) * color.a
```

Preset Color Scheme- In addition to user-designed color transfer functions, we leverage the concept of fine spatial acuity, as human eyes are more sensitive to luminance gratings compared to chromatic gratings. Accordingly, we have developed preset color schemes that ensure a uniform magnitude of incremental change in perceptual lightness. These carefully crafted color schemes contribute to enhanced detail perception, thereby improving the visualization of volumetric data.

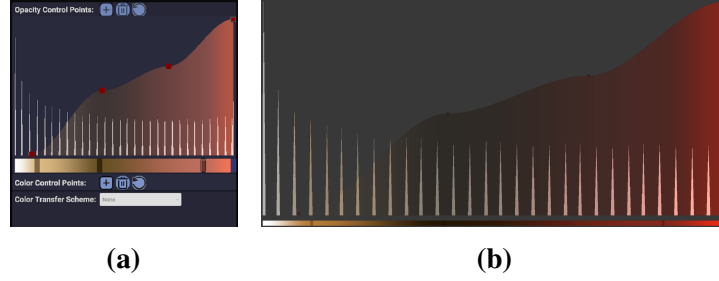


Figure 7.4. 1-Dimensional transfer function: (a)transfer function UI; (b)opacity and color mapping graph.

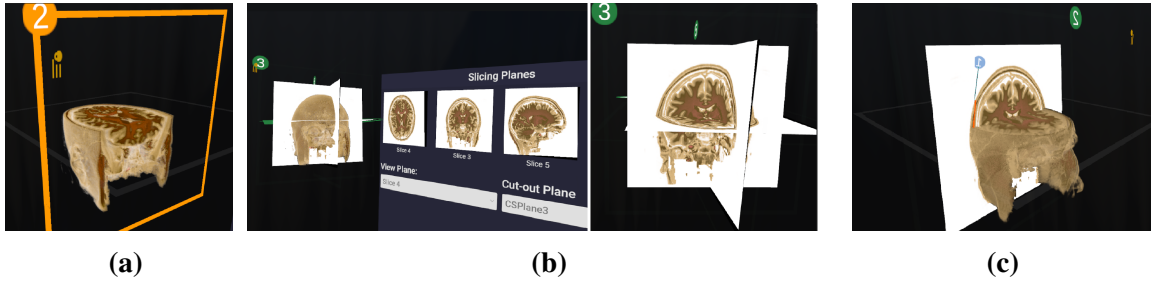


Figure 7.5. Slicing Planes: (a) Two Cut-out Planes on Volume, (b) Three View Planes with Volume and Previews on Head-up UI Panel (Left) and View Planes without Volume (Right), and (c) One Cut-out Plane with One View Plane.

7.5.3 Slicing Planes

Slicing rendering is a widely accepted technique that involves extracting 2D planes from the 3D data volume for interior analysis. To facilitate comprehensive exploration, we offer two types of slicing planes: cut-out planes (Fig. 7.5a) and view planes (Fig. 7.5b).

Cut-out Plane: By utilizing the cut-out plane, users can observe the volume being truncated at a specific location. With six degrees of freedom control over the cut-out plane, users have the flexibility to unveil hidden details in any direction and at any depth. This pre-ray-casting step acts as an additional constraint, limiting the range of ray-casting and enabling precise focus on specific regions of interest.

View Plane: The view plane provides a direct cross-sectional view at a designated location, essentially offering a 2D visualization of the dataset. This renders a single slice of the model, allowing users to examine specific regions in detail.

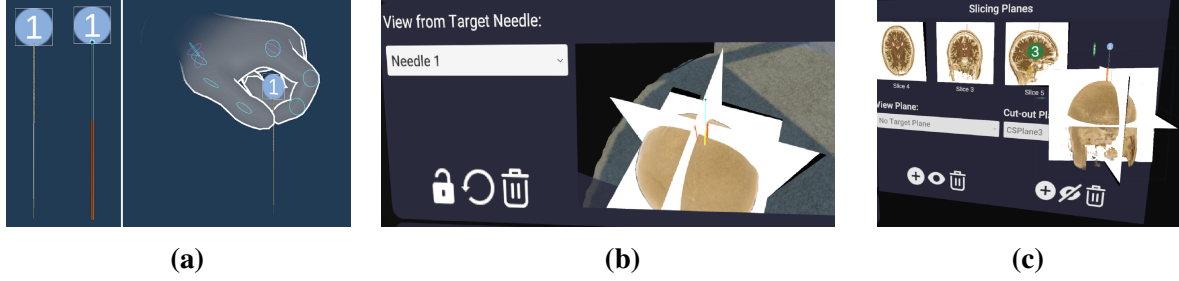


Figure 7.6. Needling Simulation: (a) 40mm Acupuncture Needles with/without Highlight (Left) and Synthesized Hand Holding the Needle in Scene (Right); (b) Top-Down View of Target Needle (Needle 1) from the Head-up UI Panel; (c) Projection of the Needle onto Three View Planes (Orange Line) with Visualization on the Head-up UI Panel.

Both types of planes can be used together (Fig. 7.5c), allowing users to examine details within the volume and utilize the view slicing plane as a guide for their needling operations, enhancing precision and accuracy.

7.5.4 Needling Simulation

We offer a variety of acupuncture needles for users to position on different parts of the body represented by the data volume. Users can simulate the process of inserting a new needle by pinching it as they would in a real scenario (Fig. 7.6a). When the needle is placed within the boundaries of the volume, it stays attached to the volume, allowing users to examine it alongside other auxiliary tools.

Multiple Views of the Target Needle- Each target needle is associated with a specific view looking down from its tail on the head-up UI panel (Fig. 7.6b). Switching between target needles automatically updates the corresponding view accordingly.

Needle Projection- When users place a needle on the data volume, they can leverage the cut-out planes and view planes to aid in comprehending the underlying structures and sense the needle's position. The view planes display the projections of the target needles, serving as visual cues to locate their positions (Fig. 7.6c). This is achieved by projecting the tip and base of the needle onto all view planes. Specifically, for a view slicing plane P with position P_p and plane normal P_n , while the needle is defined by $V_1(x,y,z)$ and $V_2(x,y,z)$. We first find the closest point

on the plane of (V_1, V_2)

$$V_c = V - ((V - P_p) \cdot P_n) \cdot P_n \quad (7.6)$$

and then project the point V_c as:

$$V_p = V_c - (V_c \cdot P_n) \cdot P_n + V \quad (7.7)$$

We then transform the projected point from the world space to the plane space to draw on the plane.

7.5.5 Standard Model Registration on Data Volumes

We performed the process of registering a standard 3D model to individual data volumes. This involved aligning and synchronizing a standard 3D model with specific data volume from CT/MRI scans:

1. For each target scope of interest in the data volume, a corresponding standard model was prepared. For example, in the case of scalp acupuncture analysis, a head 3D anatomy model was created based on head MRI scans (Fig. 7.7a).
2. Six anatomical landmarks were identified on each standard model, serving as locators that form a bounding box. These landmarks were denoted as $S_i(x, y, z)$, where $(0 < i \leq 6)$, representing 3D coordinates.
3. The corresponding landmarks on the individual data volumes were identified as $V_i(x, y, z)$, where $(0 < i \leq 6)$, ensuring spatial correspondence.
4. The registration process involved aligning the two bounding boxes formed by the standard model's landmarks ($S1 - S6$) and the corresponding landmarks on the data volumes ($V1 - V6$). This registration step ensured that the position, rotation, and scale of the bounding boxes were the same, thereby achieving a rough registration of the standard model to the data volume.

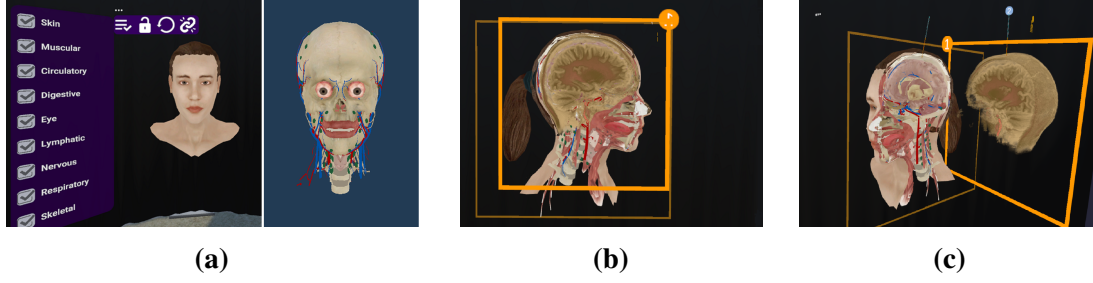


Figure 7.7. Standard Model Registration: (a) Sample Female Head Anatomy Model with Layered Anatomical Structures. (b) 3D Head Model Aligned with Data Volume, Showing Inside View with Cut-out Plane. (c) Side-by-Side Placement of 3D Head Model and Data Volume, with Cut-out Plane and Needles Positioned at the Same Relative Poses.

Fig. 7.7b illustrates when the bounding boxes on a standard model and a data volume are aligned, the existing cut-out planes and needles present in the data volume are also synchronized and applied to the standard model at the same relative pose. This synchronization is achieved through:

Listing 7.2. Synchronization between the manipulation needle and follow-up needle

```
Vector3 refLocal=refObj.InverseTransformPoint(refNeedle);
Vector3 TargetPosition=Obj.TransformPoint(refLocal);
```

Where ‘InverseTransformPoint’ transforms position (*refNeedle*, P) from world space (P_{world}) to local space of the *refObj* (P_{local}) with a 4×4 transformation matrix M .

$$P_{local} = M * P_{world} \quad (7.8)$$

and ‘TransformPoint’ inversely transforms the position (‘refNeedle’, P) from local space (P_{local}) to world space (P_{world}).

$$P_{world} = M^{-1} * P_{local} \quad (7.9)$$

This registration process facilitates the fusion of a standard 3D model with the distinctive anatomical characteristics captured in individual data volumes. Users can place the two modalities side-by-side, utilizing the standard model as a reference for needle placement (Fig. 7.7c).

7.6 Evaluation

we conducted an exploratory study that examined the following research questions:

- **RQ1.** If and how does a medical imaging-based VR system enhance acupuncture training?
- **RQ2.** If and how does AcuVR help practitioners enhance the comprehension of acupoints?
- **RQ3.** If and how does AcuVR complement the traditional learning experience of acupuncture?

7.6.1 Participants

To address these questions, we conducted a comprehensive study involving eight participants. 50% of the participants were selected from the initial iterative design session, during which they provided valuable input on desired features for a VR training system. Additionally, 50% participants were newly recruited. All the participants in our study comprised licensed practitioners or senior students who possessed basic acupuncture practice and a fundamental understanding of acupuncture and anatomy. We made this selection based on the following reasons. Firstly, our formative study revealed that entry-level students preferred a standardized model-based training system due to their relatively limited knowledge. Introducing personalized data could potentially overwhelm them. Secondly, our evaluation of AcuVR focused on challenging tasks. Senior students, who already possess basic acupuncture experience, are at a stage where they are ready to tackle difficult points and techniques. Additionally, we aimed to enable participants to compare their traditional learning experiences with learning in a virtual reality (VR) environment. All of our participants are currently engaged in the training process, either as instructors or students. In the pre-screening stage, participants were asked to rate their agreement on a 5-point Likert scale. They generally agreed (87.5% participants rate ≥ 3) that they were able to identify key structures from 3D anatomy, but disagreed (87.5% participants rate ≤ 3) that they have advanced proficiency in interpreting medical images. Any participant who has seen or tried the system (7.4) was excluded from this evaluation.

ID	Gender	Age	Professional Status*	Years of Clinical Experience	Handedness	Study Length (min)	Identify Key Structures from 3D Anatomy	Interpreting CT/MRI**	VR Experience***	Recruited from Needs-finding
P1	M	25~34	L.Ac.	6~10	Right	58	4	3	2	Y
P2	F	35~44	L1 student	N/A	Right	65	3	3	4	Y
P3	F	35~44	L2 student	N/A	Left	71	4	2	3	N
P4	Non-binary assigned female at birth	25~34	L2 student	N/A	Right	58	2	2	3	N
P5	M	25~34	L2 student	N/A	Ambidexterity	55	5	4	4	N
P6	M	25~35	L1 student	N/A	Right	58	3	3	3	N
P7	M	55~64	L.Ac.	> 20	Right	59	4	2	3	Y
P8	F	35~44	L2 student	N/A	Ambidexterity	57	4	2	3	Y

* Professional Status:

L.Ac. is the abbreviation for Licensed Acupuncturist, and L1 student represents an entry or intermediate student who has been enrolled for up to 3 years, and L2 student represents an advanced or clinical internship student.

** Interpreting CT/MRI ability level:

1-No proficiency ("I have no prior experience or knowledge in medical imaging."), 2-Limited/beginner proficiency ("I have limited experience and basic understanding of medical imaging concepts, and may need significant training or supervision."), 3-Competent/somewhat proficient ("I have basic knowledge and skills in medical imaging, but may require further training or guidance."), 4-Advanced/moderately proficient ("I have considerable experience and understanding of medical imaging concepts, including relevant certifications or coursework."), and 5-Expert/proficient ("I have extensive experience and expertise in medical imaging, including advanced certifications, and/or have completed advanced coursework or research in this area.")

*** VR Experience levels:

1-"I don't know anything about AR/VR.", 2-"I've heard about AR/VR and know what these are, but I never get a chance to try it out.", 3-"I've tried it out once or twice before.", 4-"I frequently used them for games, movies, etc.", and 5-"I consider myself as an expert for these."

Figure 7.8. Demographics of the recruited participants.

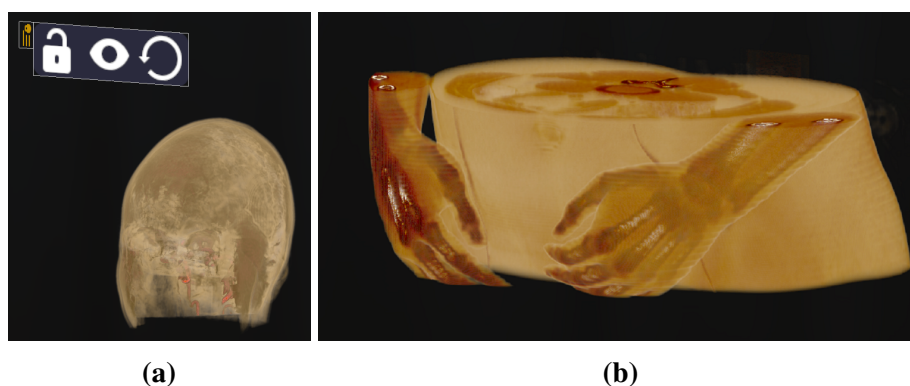


Figure 7.9. Two options for the pilot study. (a) A brain MRI and (b) a pelvis CT.

7.6.2 Before Study

With guidance from experienced doctors, we specifically choose two sample body parts for acupuncture needling: the head (Fig. 7.9a) and the pelvis (Fig. 7.9b). In scalp (head) acupuncture, needles are inserted at shallow depths into the scalp, targeting the subcutaneous layers. The special technique behind this, called *needle threading*, is to thread a thin needle through the layers of the scalp in a specific pattern or trajectory, which allows for precise stimulation of specific brain areas. Hence, it is crucial for practitioners to have a thorough understanding of the structures and functionalities of different brain areas. On the other hand,

the pelvis serves as an excellent example for demonstrating *deep puncturing* needling techniques. The target points in this area are located deep under the skin, posing a challenge even for experienced doctors to accurately locate the insertion point. Furthermore, individual variations and unique features in the pelvis present additional difficulties, making it more challenging to achieve ideal performance.

To ensure an efficient and focused study experience for the participants, we took into consideration that the majority of them were not frequent users of VR technology. To minimize their struggles with learning the system’s functionalities, menus, and user interfaces, We developed a tutorial video that included video snippets showcasing each component described in Sec. 7.5. For every component, we provided a step-by-step explanation of:

- How to navigate the system: includes the usage of buttons, sliders, and dropdown menus.
- How the provided tools assist in needling practice: include enabling visual cues and the extraction of related information.

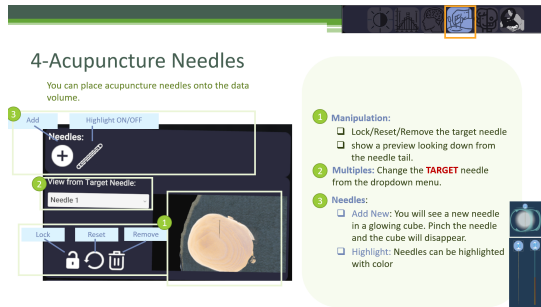
When introducing each component, we specifically utilized scalp acupuncture as an example to demonstrate its application within the system. Then, toward the conclusion of the tutorial video, we highlighted an illustrative example of needling one acupoint on the pelvis and provided a scripted practice flow as a reference. This example effectively incorporates and summarizes most of the system features.

This 20-minute tutorial video served as a comprehensive guide for participants, especially those who are new to working and practicing within a VR environment. Prior to the study, participants were required to watch this tutorial video to familiarize themselves with the system.

7.6.3 Study Procedures

We structured our study workflow as follows:

Phase 1: Setup and Introduction (5 min) Participants were first asked to completed a short pre–screening questionnaire that collects their demographic information, VR experience, and



(a) Screenshot from AcuVR tutorial video.



(b) Photo from the user study.

Figure 7.10. Settings of evaluation.

proficiency in medical imaging and anatomy. Meanwhile, we set up the system floor and boundary, the primary interaction method (controller or hand), and the dominant interaction hand (right or left) based on participants' preferences. We then provided a demonstration of the correct usage of the controller and hands within the system, recapping the content covered in the tutorial video.

Phase 2: Task-based Control Interaction (10–15 min) To guide participants through their initial VR and system exploration, we demoed to or directed the participants to perform basic actions using either controllers or bare hands within the system. For each task in Tab. 7.1 we asked participants to talk while they were trying the tasks:

Phase 3: Cognitive Engagement (20 min)

After completing the tutorial, participants were given the option to choose a specific body part (head or pelvis) for free exploration within the system. They may also follow a sample task as a guide during their exploration. We encouraged participants to engage in the *think-aloud* protocol, where they freely explored the system while verbally expressing their thoughts and observations (167). Throughout the user study, we continuously recorded videos to capture each participant's interactions. These video logs serve as valuable resources for later frame-by-frame analysis.

Table 7.1. Components and tasks in the Task-based Control Interaction phase.

Component	Task
System	Reset the system and view direction
Control	Look at your hands
	Pinch the volume to move and rotate it
	Grab the volume to move and rotate it
UI	Press the button to hide the volume
	Bring up the Volume Property menu and use the slider to adjust the minimum value limit
	Bring up the Transfer function menu, add a new color widget, and adjust its position and color
	Bring up the Slicing Plane menu, add a cut-out plane and a view plane, and manipulate their positions
	Bring up the needle menu, add a new needle, adjust its position and angle, and place it onto the volume
	Bring up the standard model menu, hide the skin, and link it to the volume

7.6.4 Post-Study Interview

After the participants completed the VR experience, a post-study questionnaire was distributed to gather their subjective experience across three dimensions: overall experience and cognitive task load (measured using the NASA-TLX (60)). Following that, we conducted semi-structured interviews to delve deeper into their questionnaire responses. Each interview lasted approximately 15 minutes and engaged in a discussion about their opinions and experiences with guided questions. The guided questions for each evaluation dimension are:

- Overall Experience
 - When you rated your overall experience as X in the questionnaire, what was your first impression or the main reason behind your high/low rating?
 - What is the most significant difference you observed when comparing VR and traditional classroom methods?
 - In what ways do you think VR could complement the traditional learning experience?
- System Usability Scale

- In what circumstances do you anticipate using this system the most?
 - Did you experience any usability challenges?
 - How do you think this system could be improved to address the challenges you encountered?
- Task Load Evaluations
 - I noticed that you rated X aspect low in the questionnaire. Could you elaborate on the specific challenges you faced in relation to that aspect?

7.6.5 Results

7.6.6 How does AcuVR enhance practitioners' acupuncture training?

On a scale of 1 to 5, participants were asked to rate their opinions on the effectiveness of VR training in aiding their ability to learn to needle the target with an enhanced comprehension of 3D acupoint and anatomy (RQ2). We also asked if they believe in themselves needle more accurately after the experience. The results showed that a considerable percentage of participants (75%) strongly agreed or agreed that VR training facilitated more accurate needling of the targets (37.5% strongly agreed, 37.5% agreed). Meanwhile, all participants unanimously expressed strong agreement (100%) that VR training enhances their understanding of acupoint and anatomy after completing the training. our takeaways are generated through thematic analysis:

Learning 3D structures in a 3D way: The unanimous agreement highlights the consistent and positive impact of AcuVR in promoting participants' comprehension and spatial understanding of acupoints and anatomical structures in a three-dimensional context. The main reason is that most acupuncture education materials are in 2D, therefore all participants appreciated the merits of seeing the 3D structures inside VR: *"I enjoy the visual, I liked the 3d aspects, feeling I'm in the body."* [P2]; *"It is visually helpful to understand in 3D, how far the needle is and where is it going into these different structures."* [P3] and also as *"a really good way to look at key structures."* [P5].

The majority of participants underscore the significance of understanding the context surrounding the acupoints, particularly those *difficult acupoints*. In acupuncture, certain acupoints pose intricacies and demand advanced skills due to factors such as anatomical location, depth, or sensitivity. Moreover, there are acupoints acknowledged as being riskier due to their proximity to vital structures or their potential for adverse reactions. For example, *“it’s especially useful for risky practice like lung, the cavity of the thorax. [P3]. Also agree with P5, “I think the key rationale is that you can visually see the context, the things that can be damaged by a needle.” [P5].*

Many participants, including P3, P4, P5, and P7, highlighted how working within the AcuVR system improved their understanding of the spatial context of nerves. For instance, P4 shared, *“I’m working with the anterior side of the iliac, and I know that around GB26 there are three nerves.”* This knowledge allows practitioners to navigate these areas with precision. Moreover, P3 emphasized the importance of employing a strategic approach: *“The goal is to stimulate the nerve without inadvertently causing a shocking pain.”* By leveraging the AcuVR system, practitioners gain valuable insights into nerve locations and can refine their needling techniques accordingly. As a medical-imaging-based VR training system, participants greatly appreciated the ability to *“see real patient’s body” [P2]* compared to the common training system that only provides a 3D anatomy model. They regarded this as *“is another dimension of the material.” [P7].* In their opinion, there is no single best format, as each format can offer specific benefits to different groups of people. As P2 explained: *“It can be really overwhelming for beginners to start with the volume if you don’t have experience with it prior to acupuncture school.”* but then she stressed that *“But the fact that you can take away layers, I think will reduce that overwhelming feeling.”*

The two different 3D representations of anatomy possess their own distinct advantages and disadvantages. Therefore when these two approaches are combined, they complement each other and enhance each other’s strengths. The enhanced medical imaging allows participants to visualize the real patient’s body, providing a more realistic experience. On the other hand,

ID	Medical Imaging Volume Alone	Standard Anatomy Model Alone	Registration of Medical Imaging Volume and Standard Model
P1	5:14	6:10	8:00
P2	9:57	0:28	22:30
P3	6:05	0	12:21
P4	10:48	5:00	18:47
P5	5:20	5:30	10:05
P6	9:59	0	18:30
P7	6:51	6:45	14:13
P8	7:40	8:30	12:05
Avg.	7:44	4:02	14:33

Figure 7.11. Time of each participant spent on the different types of 3D anatomy representation.

the traditional 3D anatomy model offers a simplified and easily navigable representation of anatomical structures. For example,

“The thing that I want to see but not quite clear here [on the CT volume] is the nerve. So it makes sense to see the one on the model.” [P7]

When reflecting on the experience with different anatomical representation formats, participants shared their preferences and observations regarding usability and learning benefits.

“I would say that the easiest one for me to use was the 3D model. I particularly liked the different menus and the ability to select the various systems in 3D. Although the CT scans are more useful, I think it requires a steep learning curve. However, by utilizing the contrast and gradient features and being able to compare different structures, students can learn about the actual structure and how it is modeled. Therefore, the 3D model is easier to grasp.” [P7]

The support of the two formats is that all the participants spent the most time seeing the registration of medical imaging and 3D anatomy model aligned together (Fig.7.11). *“I like this link feature best. Because I can’t recognize the vessel and lymph from the imaging, but I can use the model to hunt for them.” [P6]*

The following think-aloud quote exemplifies how participants utilize alignment and different layers of anatomical structures to enhance their needling technique:

“I wanted to put a needle in and then add the layers just to see if I hit anything.” (After inserting the needle) “I didn’t hit any organs, didn’t hit any bone, although it was quite close. No vessels or nerves. Fantastic.” [P2]

Understanding for Precision

Most participants believe that a deeper understanding of anatomy leads to greater accuracy in their practice. P1, a highly experienced doctor, emphasized multiple times the significance of this understanding, particularly in terms of memorizing the bones. They expressed it as follows:

“When a real person lies in front of you, you will have an X-ray vision: you can almost see the skeleton and the relationship between acupoints and bones.” [P1]

In line with the understanding, participants emphasize the need for detailed information in regions of interest for acupuncture practice. They firmly believe that *“there is no such thing as too many details, as it is crucial to capture every intricate aspect”* [P6]. For instance, when targeting the gluteal region, participants stress the significance of extensive practice to achieve accuracy while avoiding vital structures and comprehending the dynamic relationships within the area. As P2 explains, *“seeing the muscles allows you to decide whether go between them or at alternative angles, to observe their interactions. It’s especially important for orthopedic treatments”* [P2]. Moreover, experienced doctors with advanced anatomical knowledge benefit significantly from examining the deep relationships and understanding the effectiveness of specific needling techniques. For example, one participant, P7, demonstrates the integration of the 3D anatomy model and the corresponding area on the CT volume. *“[I can see] how this particular point going to affect the piriformis muscle because they are on this same layer. Now I go deeper seeing the different layers of structures and this muscle often affects sciatica... so it’s really good to see that at a particular level that they need to get to in order to affect that particular muscle.”* Additionally, practicing in VR enhances accuracy by allowing practitioners to assess the correctness of their technique by examining the needle placement underneath the skin. This capability enables them to *“check my own biases”* [P4] and gain insight into the actual depth of needling by virtually visualizing the underlying structures. As P3 expressed, this feature enables them to realize, *“I did deeper needling than I thought I was going to do by seeing virtually what those structures underneath”* [P3]. Ensuring accuracy becomes even more crucial when training students to work with patients who have special conditions, particularly related to their diseases. By training with medical imaging data, students can gain a better understanding

of the variations that arise when treating specific individuals. As P2 noted, “*Having access to the actual bone structure is essential. For example, if someone has undergone lower lumbar surgery and their vertebrae are fused, it becomes critical to avoid needling in the wrong place.*” Furthermore, when provided with an MRI scan from a patient with a brain tumor, ID1 found it to be valuable material for practicing and applying their knowledge in cancer patient treatment. They explained their approach as follows:

I can see the range of the tumor here...I would treat locally so using the lines or points above the tumor to draw qi and blood to this area. This is a different practice from the theory of general scalp acupuncture, so here I can see where is the tumor boundary and then apply the needle.

Building the confidence

Participants firmly believe that the visual reassurance provided by this tool greatly enhances students’ confidence and enables them to perform needling techniques more effectively and efficiently.

Students are really nervous when they’re needling because they don’t have an idea of particular anatomy. If they look from different angles [with this tool], it will show if it’s near any sensitive structures [P7].

Certain acupoints may be located in sensitive areas, increasing students’ anxiety about potential mistakes. For instance, in scalp acupuncture, participants expressed the benefits of using the VR tool, stating, “*With this tool I could also see even my needle goes deep, there is quite a space and it hasn’t hit anything vital*” [P5].

7.6.7 How Does AcuVR Complement Traditional Learning in Acupuncture Practice?

In traditional acupuncture needling classes, the curriculum typically consists of instructional lectures and practical sessions. During lectures, instructors utilize slides on a big screen to deliver the content, while the practical sessions involve students practicing needling techniques on each other in pairs (called “*lab partner*”), with the instructor offering guidance and adjustments. However, our participants have voiced concerns about several issues commonly

encountered in such classes. They firmly believe that AcuVR can effectively address these problems in the following manner:

Provide 3D training material

A significant challenge faced by students is the reliance on 2D materials during instructional lectures, which hinders their ability to grasp the spatial context in 3D. In the preceding section, we explored how enhancing students' understanding of 3D acupoints within their anatomical context benefits their learning and acupuncture practice. It forms the foundation for their advancement in needling techniques when treating different individuals. *"You have to be extremely familiar with needling techniques and standard anatomy at the beginning. The latter experience will be just verification of what's in your mind"* [P1]. It's also agreed by student IS1 who is in his intern stage, accumulating experience *"As long as you know the context of the point, you're just continuing to increase on your accuracy."*

Enhance Medical Imaging training:

Despite the importance of interpreting the ability of medical imaging, traditional acupuncture education doesn't extensively incorporate medical imaging training. *"It's like one hour out of the many hours"* [P3]. Consequently, it causes the fact that *"Only when someone who maybe has a Western background, they will be able to understand the patient's data better"* [P3]. This becomes particularly significant when students transition to clinical settings, where they need to diagnose and plan treatments for specific patients. *"It's a very complex process when you're assessing a patient with SI joint or lower back pain. There are a lot of different possibilities. I'm examining it right now and [I believe] If I can put my patient's body in, I can exams [some of the reasons]."*

Some students believe that incorporating the AcuVR tool into classroom instruction would not only enhance their understanding of acupoints in a 3D context but also improve their ability to interpret medical imaging (P5, P8). P5, an orthopedic practitioner, emphasized the

importance of reading imaging and stated when he was focusing on the facet joints in the system,

If a patient experiences sharp pains during rotation, it could be related to the involvement of facet joints in spine rotation. These joints may be stimulated due to necessary pressure from muscles or other factors. Short pins could be indicative of inflammation in the facet joint itself. I can identify the space between the bones in the CT scan [after tuning the parameters and cut-out planes].

Enable more hands-on practice opportunities along the class:

Participants identified three key barriers that hinder their ability to engage in hands-on needling practice:

- *“The class is super fast. You [just] learned something, and then you need to quickly do it.”* [IS1]. This little time to practice and fully comprehend the visual structures. For example, in the case of scalp acupuncture, a crucial technique in acupuncture practice, participants expressed that only 6 hours of instructional and practice time were allocated throughout the whole program. *“[This requires us] to do one technique done, move on, next one done”* [IS1].
- Cannot practice without supervision. *“It’s hard. You’re not supposed to needle outside of class [without supervision]”* [P3]. However, participants acknowledged their eagerness to practice: *“They say, don’t do it. But we all technically practice on your friends and family”* [P2]. Nevertheless, for complex acupoints and techniques, especially those involving risky areas, practicing without proper supervision can pose potential dangers. *“This [system] is like a virtual supervisor I can practice on my own”* [P6]. Meanwhile, participants highlighted the asynchrony between classroom learning and clinical practice. There is a significant gap, sometimes spanning two to three years, between when students learn in class and when they finally have the chance to practice in clinical settings near graduation. *“We have to remember everything [from class] and wait until we are in clinics. Class is like building blocks, just build, build, build. This [system] helps us improve where we’re at right now [along the class]”* [IS1].

- Unstable practice partner. Although it's beneficial to have lab partners to practice on each other, participants also acknowledge the limitations and challenges associated with this practice arrangement. Firstly, this practice arrangement can lead to unwanted side effects as each student needs to be needled multiple times. *"Some people cannot be needled because they will have headaches, or vomit because of the practice"* [P3]. Moreover, constantly switching partners makes it difficult for beginners to become familiar with different body types ([P3]). Additionally, when students are required to practice on a real body from the beginning, they often lack the confidence to perform correct practices, particularly when it comes to difficult acupoints. *"For example the eye-acupuncture, students will perform super-facial because it's hard for them to needle a point on their partner that close to the eye"* [ID2]. Therefore, students recognize this system as *"a great material for preview before needling my lab partner"* [P6].

Set up standardization and self-assessment

Another issue that arises from practicing on lab partners is the inherent challenge of dealing with partners who have special issues or conditions. Each lab partner may present with unique characteristics or health conditions that can affect the needling process. As expressed by P3:

Our lab partner could have all kinds of special issues like my partner who has scoliosis, I need to know how to needle a healthy one, how it feels in palpation compared to the scoliosis one first and then figure out the point also curved. Setting the standard with a healthy body. So then we can see the disease and the illnesses when we're treating patients.

At the initial stages of learning, it is vital to establish a standardized understanding of what a healthy body looks and feels like. This provides students with a foundation to adapt their knowledge to different individuals, which is challenging to achieve in current classes.

Fortunately, public datasets and resources offer materials that showcase standardized human body cases. Combined with the standard 3D modeling in AcuVR, these resources provide a framework for teaching and setting standards in acupuncture education.

Combine the strength of traditional class and AcuVR

Palpation plays a crucial role in acupuncture as it allows practitioners to localize the skeletal landmarks and assess the patient's condition thus identifying acupuncture points, and detecting subtle changes in the body. The training process for palpation in acupuncture involves hands-on practice and the development of tactile sensitivity through direct interaction with patients. *"You will need a human body that is able to palpate and reflect back to the contents in VR."* [P2]. Doctors who teach needling classes also express the same concern. For example, *"If I have this for my students, I will ask my students to practice, but not only in VR but engaging the real body for palpation in the same time"* [P1].

Due to the challenges of replicating tactile sensations and nuances in a virtual environment with a bare hand and no extra device, there is a consensus among participants that integrating palpation lectures training with training in VR could be beneficial, either during the class(synchronously) or later outside the class(asynchronously).

Many students (P4, P5) raised the point that they want to have this system available in class along with the lecture for instructional purposes. *"We'll be engaged if using it in the class. We can watch the professor [operate] and the professor can also connect to their model [in the real world]... And then [if] student asked questions the professor would move the needle, move those [anatomical] structures while explaining"* [P5]. This gives the instructor higher requirements to link the body in front with the visualization in the system. In fact, the participants already demonstrated their ability to give instructional lectures using the VR system, providing insights into their decision-making process. For instance, P7 explained his thought process while placing a needle on the lower back area, demonstrating how the system could be used as a teaching tool:

I'm moving the plane over here, observing how moving through different planes is affecting the view. [I'm interested in] the sacrum and how it's attaching to the pelvic structure. I'm observing the sacroiliac joint as well. In the image, you have the butterfly, and the upper part of the wing attaches to the sacrum. That's the sacroiliac joint. In the middle, you see where the lumbar region is. The

needle placement looks somewhat correct but superficial. It would be different if I change the angle a little.

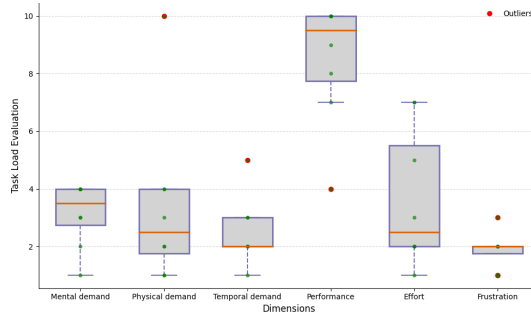
To provide students with a more realistic experience, P7 suggests that we should further “*let the surface reacts to the palpation*”, which is to use visual clues to represent and simulate the palpation students can be trained to feel. These visual cues would allow students to develop a sense of touch even without physically touching a real body. This is especially important to train the students with the bony landmarks, even if they are not touching a real body the same time they’re using the system, “*having some visual outside would be good. New students then can build their own confidence in navigating the body*” [P4].

7.6.8 System Evaluations

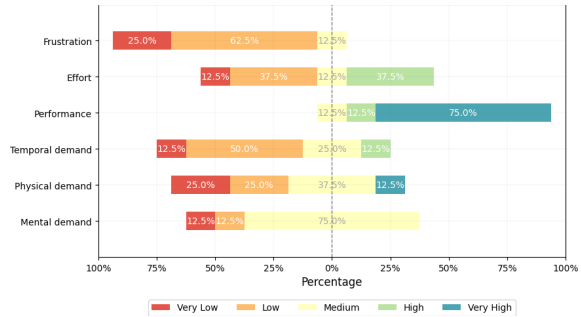
Overall, on a scale of 1 to 5, participants unanimously reported 100% satisfaction with the AcuVR experience. This high satisfaction rate was reflected by 50% of participants strongly agreeing and the remaining 50% agreeing with their experience. Fig. 7.12 the results of task load evaluation (TLE) in six dimensions: frustration, effort, performance, temporal demand, physical demand, and mental demand. Specifically, Fig. 7.12a shows the response distribution in standard box plots. Fig. 7.12b shows the same distribution interpreted with the Weighted Workload category (WWL) (34), centered around the medium ratings; lower ratings are shown on the left side in warmer colors, and higher ratings are shown on the right side in colder colors. As we can see, most participants consider the system highly performant and easy to use, i.e. low mental, physical, and temporal demands, and minimal frustration. The majority of the participants think the system requires a reasonable amount of effort to use and are satisfied with their performance.

The participants’ comments revealed two main themes related to the usability evaluation of the overall system: ease of use and well-designed integration of functions.

Regarding ease of use, participants expressed positive feedback. “*There is not too steep a learning curve at all. I feel comfortable with the user interface*” [P2] and “*I feel I pick it*



(a) Standard box plots.



(b) Weighted workload category plots.

Figure 7.12. Responses to the Task Load Evaluation

up easily” [P3]. The majority of participants believed that most people could easily use the system. Therefore, P4 and P6 highlight the various potential uses of the system, such as, “It’d be awesome to have this available in the library” [P4] and “deploy on campus for people to try” [P6]. Furthermore, P5 and P8 praised the needling experience, emphasizing its quality and smoothness. In particular, P8 stated, “Needling is my favorite feature. It was beautifully done, and the needling was very smooth” [P8].

Regarding the well-designed integration of functions, participants emphasized the benefits of both the standard model and medical imaging. Participant 3 noted, “It’s much better that you get to know the structured anatomy... moving to this individual.” P7 expressed difficulty in fine-tuning the parameters, stating, “I didn’t tune it because I’m afraid I don’t know how to... without segmentation, it would still not be straightforward for him to recognize the structure.” He further added, “The imaging is difficult to see the difference in the structures unless you know exactly because they’re not different colors.”

In summary, the thematic analysis highlighted participants’ positive perception of the system’s ease of use, with comments on the user interface and the potential for diverse applications. Participants appreciated the well-designed integration of the standard model and medical imaging. However, challenges were identified regarding fine-tuning parameters and the need for clearer visual distinctions in structures. Incorporating these insights can further enhance the usability and effectiveness of the system for users.

7.7 Discussion

The results of our study indicate that the medical imaging-based VR system (RQ2) utilized in AcuVR effectively enhances acupuncture training by providing learners with a unique opportunity to comprehend 3D structures in a three-dimensional manner (RQ1). This immersive approach enables students to gain a deeper understanding of acupoints by visualizing their context more accurately, leading to improved precision in practice. By combining the strengths of standard anatomy modeling and real patients' data, the VR system offers learners a comprehensive learning experience. The ability to examine needle placement underneath the skin in real-time provides immediate feedback, enhancing learners' awareness of the correctness of their technique and fostering self-assessment. Notably, the VR system proves particularly valuable for training practitioners who encounter patients with special issues related to their specific diseases. The simulation of various patient scenarios equips learners with the skills needed to adapt their acupuncture techniques accordingly, ultimately enhancing patient care and treatment outcomes.

The findings of our study also demonstrate that AcuVR effectively complements traditional learning in acupuncture practice (RQ3). By providing 3D training materials, AcuVR offers an immersive and interactive learning experience, enabling practitioners to develop a deeper understanding of acupoints and their anatomical structures. The VR system also facilitates increased hands-on practice opportunities, improving skill acquisition and muscle memory. Additionally, AcuVR promotes standardization and self-assessment through predefined benchmarks and immediate feedback. It serves as a valuable supplement to traditional classroom teaching, combining theoretical knowledge with interactive modules to reinforce understanding and cultivate a comprehensive approach to acupuncture practice. Integration of AcuVR in acupuncture education enhances practitioners' proficiency and learning outcomes, contributing to the advancement of acupuncture practice.

Because it's easy to deploy and use without technical assistance, AcuVR can be seam-

lessly combined with traditional classroom teaching in several ways:

- **Off-class self-training:** It can be used either as a preview before the class or for unsupervised practice after the class. This allows practitioners to independently explore and reinforce their understanding of acupoints and their anatomical structures
- **Integrated into the instructional process during class:** Instructors can utilize the VR system to demonstrate acupuncture techniques on a real body while simultaneously showing the internal structures through the VR interface. This interactive approach enhances the learning experience and provides a comprehensive understanding of the practical application of acupuncture.
- **Deployed in school public spaces:** This allows practitioners to utilize the system whenever they need to discuss specific patients, acupoints, or treatment plans. It serves as a convenient tool for quick reference and collaborative discussions among practitioners.

7.7.1 How to use Medical Imaging the right way

Despite the numerous benefits of integrating medical imaging into AcuVR, one notable limitation is the challenge faced by acupuncture students and doctors without a Western medical background in interpreting and understanding the detailed anatomy presented in medical imaging. As a training system, it is imperative to provide better enhancements and auxiliary tools to facilitate easier learning. While participants generally provided positive feedback regarding working with medical imaging using the tools provided in AcuVR, they also expressed concerns about the learning curve and uncertainty associated with using the transfer function toolbox. To address these issues and further improve the user experience, we are considering the following enhancements in future work:

Design Transfer function scheme for different scenarios During our study, P7 expressed hesitation in adjusting the rendering settings of CT/MRI scans due to a lack of familiarity. However, when we demonstrated a fine-tuning of the transfer function to unveil the colon in

abdominal imaging, he acknowledged an improved ability to recognize the structure. It is worth noting that without proper segmentation, identifying the structure would still be challenging.

In the case of acupuncture, different acupoints may involve varying local structures of interest. While bones often serve as common landmarks, organs, muscles, and specific pathologies also play an important role. Extracting fine structures from CT scans can be particularly challenging, requiring settings tailored to meet the requirements of individual users. AcuVR's current functionality addresses this issue through the registration of a standard model onto medical imaging. This registration aids in better visualizing fine structures within the context of the registered model.

In future work, it is essential to further refine the registration between the standard model and medical imaging to enhance users' perception of fine structures. Additionally, designing user-friendly tools that allow for easy customization of the transfer function, specifically tailored to the structures of interest, would significantly enhance the interpretation.

Segmentation and reconstruction from medical imaging

Another area of future improvement for AcuVR is the implementation of dynamic segmentation and reconstruction techniques from medical imaging. This advanced feature would enable the automatic segmentation and reconstruction of key anatomical structures, enhancing the intuitive understanding of acupoints and their surrounding structures. Additionally, the integration of segmentation will enable collision detection between acupuncture needles and critical structures. Real-time feedback and alerts would be provided to users, allowing them to correct their technique and ensure safety.

7.7.2 Evolving AcuVR: Paving the Way for System Improvement

By observing participants working in AcuVR, we gained valuable insights and identified areas for future improvement. These observations have provided us with new ideas and considerations for our future work. Some of the key aspects we plan to address include:

Visual-based Palpation Simulation in Virtual Reality An important aspect of evolving

AcuVR is the development of visual-based palpation simulation in virtual reality. While one option for enhancing the palpation simulation is the incorporation of haptic feedback using specialized devices such as haptic gloves or controllers, this approach does have drawbacks. It requires additional setup, maintenance, and expense, and may not fully replicate the tactile sensations experienced during palpation. Furthermore, haptic devices can impose physical constraints on hand movements.

An alternative approach that shows promise is the utilization of accurate real-time hand tracking. By employing advanced hand tracking technologies, AcuVR can detect the precise placement of the user's hand on virtual contents, such as the skin of the standard anatomy model or the 3D reconstructed CT/MRI scan. When the user places their hand on the virtual content, it should automatically highlight the underlying bony structure beneath, which closely mimics the palpation technique used in the real world. This approach potentially will provide a more natural and unrestricted interaction.

Understand the context in a more dynamic way Another aspect that is currently missing in the AcuVR system is the ability to understand the context of anatomy and acupoints in a more dynamic manner. While pre-scanned MRI/CT images cannot capture the dynamic movements of the body, there is potential to incorporate dynamic changes in the reconstructed models and standard 3D models. By introducing interactive elements that demonstrate how the anatomy and acupoints change during movement or specific conditions, learners can develop a more comprehensive understanding of the dynamic nature of acupuncture practice. This could involve showcasing variations in muscle tension and joint movement.

7.7.3 Limitation

One limitation of the user study was the variation in participants' familiarity with the VR training system. While efforts were made to inform all participants about the features and operation of the system before allowing them to explore freely, there were instances where some participants had watched the tutorial video prior to the study while others had not. This

discrepancy in prior knowledge resulted in a difference in participants' initial understanding and comfort level with the system. Those who had not watched the tutorial video often expressed feeling overwhelmed as they were still in the process of learning the system during the study. This discrepancy in familiarity highlights the importance of ensuring consistent training and preparation for all participants in future studies, to minimize any potential biases and ensure a level playing field in evaluating the system's effectiveness and usability.

7.8 Conclusion

In this paper, we presented AcuVR, a pioneering virtual reality acupuncture training system that incorporates personalized medical imaging. Through a pilot study, we explored the potential of AcuVR to enhance acupuncture training and improve the comprehension process while complementing traditional learning approaches. The feedback from our users indicates that AcuVR is easy to use, informative, and intuitive, showcasing its potential to benefit students in their advanced needling classes. By integrating medical imaging into the training system, AcuVR offers a novel approach that enables students to gain a deeper understanding of acupuncture techniques and acupoint locations. The positive reception and user ratings demonstrate the promising future of AcuVR as an invaluable tool for enhancing acupuncture education. As further advancements and refinements are made, AcuVR holds great potential to revolutionize acupuncture training and contribute to the development of skilled acupuncture practitioners.

7.9 Acknowledgments

Chapter 7, in full, is currently being prepared for submission for publication of the material. Menghe Zhang, Chen Chen, Matin Yarmand, and Nadir Weibel. The dissertation author was the primary investigator and author of this paper.

Chapter 8

Conclusion

In this dissertation, we demonstrate the potential of using XR to assist practitioners and students in invasive medical procedures. We further show that extensive studies in needs finding and custom design are needed to adapt XR technology to each type of invasive medical procedure.

In Chapter 1, we started with the potentials of using XR to assist today's invasive medical procedure with enhanced 3D imaging, as well as the challenges and design considerations. We discussed the existing landscape of XR in medical procedures, integration of medical imaging in XR, interaction with 3D objects in XR, and its impact on acupuncture, a specific type of invasive medical procedure.

In Chapter 2, we described CalAR, a new Android AR framework that combines AR-Core's tracking system with a 3D menu system, a physics engine, and environment-based lighting. CalAR enables software developers to easily build their own AR applications, and can automatically adapt to a variety of VR systems.

In Chapter 3, we described a server-aided DICOM viewer for Android mobile devices. We integrated several core features requested by medical professionals, including rendering parameters, volume cutting, organ masks, as well as real-time streaming using a server. Our experience shows that by incorporating an additional server, we can dramatically improve user experiences by offloading computation tasks and providing auxiliary data. Future research can be

devoted to the development of a better multi-user collaboration experience in augmented reality (AR) scenarios.

In Chapter 4, we extended the previous Android-based DICOM viewer to a Mixed Reality setting and built a prototype on HoloLens 2. We ported the same set of features from Android to HoloLens, while optimizing for this two-views head-mount display system. This provides smartphone users with a seamless experience of remote control and also enables new possibilities like cross-platform collaboration. In the process, we also discovered that careful design and parameter tuning are needed on this new platform, in order to achieve the best balance between performance and quality.

In Chapter 5, 6, 7, we focus on acupuncture, a specific type of invasive medical procedures, and explored the requirements and design considerations for leveraging XR to enhance training and treatment process in acupuncture.

In Chapter 5, we proposed E-FaceAtlasAR, a facial acupuncture assistance AR system that assists users with little experience in self treatments like self-acupressure. We found that naively using traditional methods can lead to high inaccuracies in acupoint localization, and further research is needed to improve accuracy and potentially enabling needle tracking in AR settings.

In Chapter 6, we performed a need-finding analysis on how to introduce immersive visualizations in VR to empower medical acupuncture doctors and students. We surveyed 17 participants, discussed the challenges and design opportunities and reports 11 barriers, which leads to several key design factors among five tasks. We showed that by adapting existing VR visualization and interaction technologies, we can empower acupuncture practitioners in their daily routine.

In Chapter 7, we presented AcuVR, a groundbreaking VR acupuncture training system with personalized medical imaging. In a pilot study, we assessed AcuVR's potential to improve acupuncture training, enhance comprehension, and complement traditional learning methods. User feedback indicates that AcuVR is user-friendly, informative, and intuitive, particularly

benefiting students in advanced needling classes. By integrating medical imaging, AcuVR offers a novel approach to a deeper understanding of acupuncture techniques and acupoint locations. The positive reception and user ratings highlight AcuVR's promising future as a valuable tool in acupuncture education. With ongoing advancements, AcuVR has the potential to empower acupuncture training and foster skilled practitioners.

This dissertation presents a compelling exploration of personalized medical imaging-based XR systems to enhance the comprehension and performance of invasive medical procedures by tailoring the design to task- and people-specific principles. Our findings suggest that these systems can be most effective when they accommodate diverse levels of interpretation ability among clinicians. Throughout the dissertation, each project adheres to task- and people-specific design principles. Chapters 2 to 5 primarily delve into development and engineering techniques, while Chapters 6 and 7 shift the emphasis towards adopting user-centered design approaches.

On the engineering side, when designing XR systems designed for medical use, it requires careful consideration of the development approach, with one crucial decision being the choice between utilizing off-the-shelf engines like Unity/Unreal or building on the native platform. For instance, in Chapters 2, 3, 4, and 5, we introduced three XR systems developed directly on native platforms, specifically Android (covered in Chapter 2, 3, and 5) and Universal Windows Platform (explored in Chapter 4). In Chapter 7, we prototyped a VR training system using Unity.

Generally, opting for Unity or Unreal can simplify the development process when targeting a diverse range of devices and fast prototype with rich user interactions. However, if the application focuses on a specific platform that provides robust native tools and features tailored to medical applications, building on the native platform may be more suitable. Also, if the application needs to incorporate state-of-the-art machine learning models and algorithms, off-the-shelf game engines could be less flexible and hard to customize to use these new techniques. In such cases, building on the native platform provides greater flexibility for incorporating and refining advanced machine-learning techniques specific to the medical domain.

Another important consideration is the performance requirements. Unity and Unreal

Engine are widely recognized for their capacity to handle complex graphics rendering, physics simulations, and computationally intensive tasks. Generally, these mature frameworks can provide decent rendering and physical simulation performance and help avoid reinventing the wheel. However, this may not be the best approach if performance is a critical goal of the system, and manual tuning or optimization is required; in that case, building on the native platform may offer greater flexibility and control in terms of optimization.

Additionally, a comprehensive system typically requires the integration of external systems and libraries. For instance, a medical imaging application may need a library to encode and decode specific patient data formats, such as DICOM files. It is essential to consider the third-party support available for such libraries, including the programming languages they are compatible with (e.g., C++, Python, or others), and their ability to seamlessly integrate as plugins or be imported into the pipeline when designing with game engines.

Overall, when designing an XR system for medical use, designers need to decide the general engineering path considering the functionalities, platform compatibility, performance requirements, customization, and integration needs. It is crucial to identify the critical factors and the primary objectives of the system to determine the appropriate engineering path first before delving into the development.

On the user-centered design side, despite employing user-centered design approaches and conducting iterative design sessions involving doctors and students, some participants encountered challenges during the initial adaptation to the VR system's learning curve and understanding of medical imaging. They expressed experiencing effort and mental demands during this phase.

The results emphasize that the design should accommodate diverse levels of interpretation ability among clinicians to maximize the benefits of medical imaging. Traditionally, these systems have primarily catered to Western medical tasks, like surgical planning (Chapter 3 and 4), targeting radiologists and surgeons who are well-versed in interpreting and utilizing medical imaging on a daily basis. Therefore, these experts feel confident and comfortable when adjusting

the visualization of patient scans within these systems.

However, it is crucial to acknowledge that not all clinicians share the same level of exposure or expertise in medical imaging. For instance, acupuncture doctors, while recognizing the importance of medical imaging within their practice, may not require it on a daily basis. Nevertheless, they still rely on these systems as a valuable component of their clinical toolkit. To ensure inclusivity and usability, designers must provide better support to these clinicians, making key components more intuitive and straightforward.

In essence, the primary goal of XR systems should be to provide robust support and aid to the target group, removing any potential barriers or limitations that might hinder their effective use. By prioritizing accessibility and user-friendliness, designers can empower clinicians of varying backgrounds and specialties to leverage the full potential of medical imaging-based XR systems, ultimately enhancing patient care and medical outcomes.

Overall, this dissertation conclusively demonstrates the necessity of specialized XR systems to cater to the specific needs of diverse medical procedures. Through the exploration of various treatments, we have expanded the horizons of XR's potential in medical settings, broadening its scope of use. This is only the beginning of an exciting journey. While the full potential of XR devices and applications in consumer-level products is yet to be fully realized, the healthcare industry has emerged as a shining example of successful XR integration. The adoption of popular MR headsets by enterprises in healthcare has not only demonstrated their efficacy but also highlighted their affordability and practicality in daily use. As XR continues its rapid evolution, I firmly believe that it will play a transformative role in simplifying invasive procedures, enhancing accessibility, and revolutionizing the field of healthcare.

Appendix A

Questionnaire for Chapter 6

A.1 Pre-Screening Questionnaire

This section provides the full pre-screening questionnaire for the participants.

Pre-screening Questionnaire

1. Your Preferred Name

2. Your Gender
☐ Female ☐ Male ☐ Prefer not to say ☐ Others
3. Your Age Group
☐ 18~24 ☐ 25~34 ☐ 35~44 ☐ 45~54 ☐ 55~64 ☐ >65
4. Your Professional Status
☐ Student ☐ Resident ☐ Licensed or Certified Acupuncturist ☐ Others
5. How many years have you been practicing acupuncture(post-internship)?
☐ <2 ☐ 3~5 ☐ 6~10 ☐ 11~20 ☐ >20
6. Is your practice
☐ Non-teaching hospital based ☐ Non-teaching hospital based ☐ Individual practice
☐ Small group practice (5 or fewer physicians) ☐ Large group practice (6 or more physicians) ☐ Others
7. How often do you work with students or assistants?

	0	1	2	3	4	5	6	7	
Never	☐	☐	☐	☐	☐	☐	☐	☐	Every day
8. How often do you have discussions with other doctors?

	0	1	2	3	4	5	6	7	
Never	☐	☐	☐	☐	☐	☐	☐	☐	Every day
9. How often do you explain the treatment plans to your patients?

	0	1	2	3	4	5	6	7	
Never	☐	☐	☐	☐	☐	☐	☐	☐	Every day
10. On what scale do you describe yourself as good at interpreting Medical Imaging(MRI, CT, ULTRASOUND, etc.)?

	0	1	2	3	4	5	6	7	
Never	☐	☐	☐	☐	☐	☐	☐	☐	Every day
11. How often do you use/refer to patients' medical imaging(MRI, CT, ULTRASOUND, etc) in your practice?

	0	1	2	3	4	5	6	7	
Never	☐	☐	☐	☐	☐	☐	☐	☐	Every day
12. In what scale do you think it would help if you have patients' medical imaging(MRI, CT, ULTRASOUND, etc) in your practice?

	0	1	2	3	4	5	6	7	
Never	☐	☐	☐	☐	☐	☐	☐	☐	Every day
13. Please rate your past experience of using head-mounted Virtual Reality (VR) or Augmented Reality (AR)
☐ I don't know anything about them
☐ I've heard about them and known what are these. But I never get a chance to try it our.
☐ I've tried it out once or twice before.
☐ I frequently used them for games, movies, etc.
☐ I consider myself as an expert for these.

Figure A.1. The 13-question pre-screening questionnaire.

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