Diegetic User Interfaces in Extended Reality for 3D Medical Visualization

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***Abstract*—The integration of 3D anatomical models derived from DICOM images into extended reality (XR) interfaces significantly enhances the visualization and interaction with anatomical data, particularly in educational, pre-operative, and intra-operative medical scenarios. This paper presents an XR application developed with Unity 3D for the Meta Quest 3, enabling concurrent visualization of DICOM images and interaction with the 3D model in an immersive XR environment. The application incorporates an advanced diegetic user interface, allowing users to manipulate the 3D model intuitively through hand gestures for actions like annotating, dragging, dropping, and scaling objects. Utilizing a virtual tablet and slider, users can precisely control DICOM slice planes that intersect the 3D model, providing real-time updates of visual content. Enhanced by hand tracking, this interface aims to facilitate the natural manipulation of cross-sectional views, thereby optimizing anatomical visualization.**

***Index Terms*—Extended Reality, DICOM Images, 3D Slicer Software, 3D Anatomical Models, Medical Imaging, Diegetic Interfaces**

I. Introduction

Digital Imaging and Communications in Medicine (DICOM) has become the standard for handling, storing, printing, and transmitting information in medical imagery [24], [34]. DICOM images provide detailed views of internal body structures; however, their 2D nature poses significant challenges in analysis and interpretation [15], [20]. Clinicians often work with 3D anatomical structures but typically analyze data from 2D DICOM images, thus their workflow presents several challenges [15]. The primary issue is the loss of spatial context, as 2D slices do not convey the full 3D relationships between anatomical features. This can lead to difficulties in accurately diagnosing conditions, planning surgeries, and understanding complex structures. Additionally, interpreting 2D images requires significant expertise and can be time-consuming, as doctors must mentally reconstruct the 3D anatomy from multiple 2D slices. This process is prone to errors and can overlook clinically significant details [13], [20], [21].

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For all these reasons, much 2D-to-3D software has been developed, such as 3DSlicer [10] and OsiriX [29], to visualize, process, and convert medical imaging data (e.g., DICOM images) into 3D models. The integration of these 3D models reconstructed from DICOM images finds extensive applications in various clinical settings [8], [28]. In medical education, 3D models serve as powerful tools for anatomical visualization and understanding complex structures, thus significantly enhancing the learning experience for both students and professionals [3], [27]. Pre-operative planning benefits greatly from these models, as they provide detailed anatomical insights, allowing surgeons to strategize and practice complex procedures with higher precision [35]. During intra-operative procedures, real-time visualization of 3D models can guide surgeons, improving accuracy and outcomes [4], [6]. However, a major challenge is synchronizing multi-modal data, enabling the simultaneous visualization of DICOM slices, 3D models, and the physical scanned object. This requires software with advanced capabilities that offer efficient and intuitive user interfaces, as their usability significantly impacts the efficiency and effectiveness of clinical workflows [9].

Extended Reality (XR) presents a promising solution to this challenge [12], [36] due to its capability to integrate virtual and physical elements, offering enhanced visualization and interaction possibilities. However, the effectiveness of XR applications is mostly related to the choice of the interface design [1], [33]. Diegetic User Interfaces (DUIs) are particularly relevant in the realm of XR [32], where they integrate virtual objects with the real-world environment, creating a natural and integrated user experience. Unlike non-diegetic interfaces that project information onto separate screens, DUIs embed digital content within the user's immediate surroundings. In XR medical imaging, DUIs utilize spatial context to significantly enhance the clinician's workflow. They establish a cohesive environment where medical data such as 2D DICOM images and 3D anatomical models coexist and interact with both each other and the physical surroundings. DUIs can overlay DICOM images and 3D models onto physical objects or environments, facilitating intuitive interaction and enhancing understanding of complex anatomical structures. This spatially aware approach is crucial for medical education and surgical planning, enabling clinicians to manipulate, annotate, and analyze medical data directly within their field of view. By doing so, DUIs reduce cognitive load and enhance spatial understanding, thereby improving the efficiency and accuracy of clinical tasks [30], [31], [37]. Meta Quest, a leading device in the XR field, provides robust capabilities for creating immersive and interactive environments. Its integration into medical education and practice facilitates the development of applications that merge virtual models with physical reality, offering new insights and capabilities in medical imaging and education [11], [23].

This paper contributes to the implementation of a diegetic interface in XR using Meta Quest 3 as a device. The implemented interface utilizes a visualization approach with ”tablet” and ”slider” controls to simultaneously display DICOM images, 3D models and real objects. DICOM images are tightly linked to the 3D model through the slider control, enabling synchronized visualization. The interface, in particular, is inspired by a tool well-known in the medical field—especially in neurosurgery—namely the neuronavigator [14]. Furthermore, the system also integrates an annotation feature for DICOM images, with the annotation content directly displayed on the 3D model for context-aware exploration. We describe and explore the system architecture, the interaction mechanisms, and the clinical workflow integration, stressing how this approach can revolutionize the analysis and interpretation of medical images in an educational setting. The potential benefits and challenges of adopting diegetic user interfaces in medical XR applications are also examined, highlighting the transformative impact on healthcare technology.

II. Related Works

XR has become an increasingly valuable technological tool in medical imaging, enhancing visualization and interaction with anatomical data. Previous research has demonstrated XR’s potential to provide clinitians with intuitive and immersive ways to view and manipulate medical images and 3D models in educational, pre-operative and intra-operative settings.

Notable examples include XR systems that superimpose 3D models of anatomical structures onto a patient’s body, facilitating real-time guidance during surgical procedures [2], [7], [25]. Additionally, XR systems enable the visualization of patient-specific 3D models derived from DICOM images. Integrating these 3D models with 2D DICOM images allows clinicians to correlate different anatomical views in real-time, thereby enhancing their understanding of spatial relationships between various anatomical structures, which is crucial for accurate diagnosis and treatment. This approach has proven particularly beneficial in cardiac, brain, and skull segmentation [26]. Furthermore, XR applications can offer omnidirectional slicing capabilities, allowing clinicians to interactively explore and annotate 3D models from any angle [18], [19]. However, integrating 3D models with 2D DICOM slices involves complex image registration techniques that demand precise alignment to ensure accuracy.

The real-time alignment and merging of different imaging modalities can be computationally intensive, often necessitating advanced hardware and sophisticated algorithms. Previous studies have explored these challenges. For example, one study [12] describes a system that automatically generates 3D models from DICOM images, which are compatible with any XR-HMDs, to facilitate brain tumor segmentation and visualization. Another study, the development of CardiacAR, an iOS XR application, enhances cardiovascular surgical planning by enabling interactive, omnidirectional slicing and virtual annotation of 3D heart models, thereby overcoming the limitations of traditional physical heart model cuts [17]. Similarly, [36] introduces a prototype holographic XR DICOM Viewer for the Microsoft HoloLens 2 (HL2), transforming preoperative medical imaging data, typically stored as 2D DICOM images from CT and MRI scans, into immersive 3D visualizations. This enhances surgical planning through real-time rendering and interaction with volumetric datasets in augmented reality. Furthermore, [11] explores using XR for preoperative planning in thoracic surgery, emphasizing 3D imaging and real-time visualization for enhanced surgical strategy development using the Meta Quest device.

Concerning the choice of the device, the results presented in [23] indicated no significant differences in ergonomics, ease of use, or visual clarity between the HoloLens and Meta Quest. However, the participants noted a smaller field of view with the HoloLens, which can be a notable downside. Moreover, recent developments have highlighted some advantages of using devices like the Meta Quest 3 over more advanced and costly options like the HoloLens. The Meta Quest 3 offers superior color rendering for enhanced anatomical visualization, improved hand-tracking capabilities crucial for precise interaction, and is more cost-effective compared to the HoloLens. Its simpler application development and standalone nature further facilitate easier integration into medical settings, potentially revolutionizing surgical planning with high-quality, affordable visualization tools. These advantages suggest that devices like the Meta Quest 3 could play a significant role in the future of medical imaging and surgical planning, offering a more practical and accessible solution for integrating AR into clinical workflows. Despite advancements in XR and 3D imaging, there remains a critical gap in the literature regarding the efficient and scalable integration of 3D models with 2D DICOM images and the adoption of Meta Quest devices in such field has not been well investigated.

III. The system

The creation of 3D models from medical imaging data, particularly 2D DICOM images, is critical for various applications in medical research, diagnosis, and treatment planning. In our system, the 3D model of a synthetic skull is reconstructed using 3DSlicer [10], a software widely used for medical image analysis and visualization. Then, the model developed within Unity 3D for Meta Quest 3. This application allows users to interact with the 3D model of the skull within an XR environment.

The main features of our system include:

A Scaling, dragging and dropping the 3D model using hand gestures.

B Interacting with a diegetic interface that includes a virtual tablet with a virtual slider to visualize the DICOM images, the 3D model, and the real synthetic skull within the same field of view.

C Annotating DICOM images and visualizing the annotation directly on the 3D model.

Each of these features is described in detail below.

A. 3D model creation and simple hand interactions

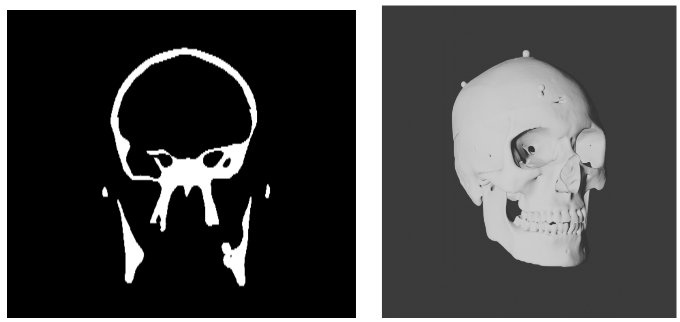
The methodology for generating accurate 3D models from DICOM images is built on leveraging the powerful capabilities of 3D Slicer [10], [16]. This subsection outlines the key steps involved in the segmentation process, validation of model accuracy, and the interactive functionality provided by the implemented system, along with technical enhancements for usability and performance.

1) 3D Model Generation and Segmentation Process: The initial subject analyzed was the skull of a model used by neurosurgeons for training purposes. However, with minor adaptations, the same methodology can be applied to human patients. The first step in creating the system was to generate a precise 3D model derived from 2D diagnostic images, such as Computed Tomography (CT) scans and Magnetic Resonance Imaging (MRI), stored in DICOM format. Using 3D Slicer [10], [16], the DICOM images were segmented to isolate the model skull with high precision. The segmentation process employed the threshold tool with an automatically determined range, allowing the extraction of the skull's key anatomical features. Once segmentation was complete, the 3D model was exported in OBJ format, a widely accepted standard for 3D printing and virtual modeling (see Fig. 1).

To ensure model accuracy, iterative refinement, and quality checks were performed throughout the segmentation process. Fine-tuning ensured that each DICOM slice was correctly mapped to its spatial position within the 3D volume. This was achieved by dividing the volume into slices based on the total number of images in the scan and performing a slice-by-slice adjustment to align the reconstructed model precisely with the original diagnostic images. The resulting 3D model maintained the maximum resolution attainable from the DICOM data, resulting in a highly detailed but computationally heavy structure. For standalone devices like the Meta Quest, the performance limitations necessitated optimization.

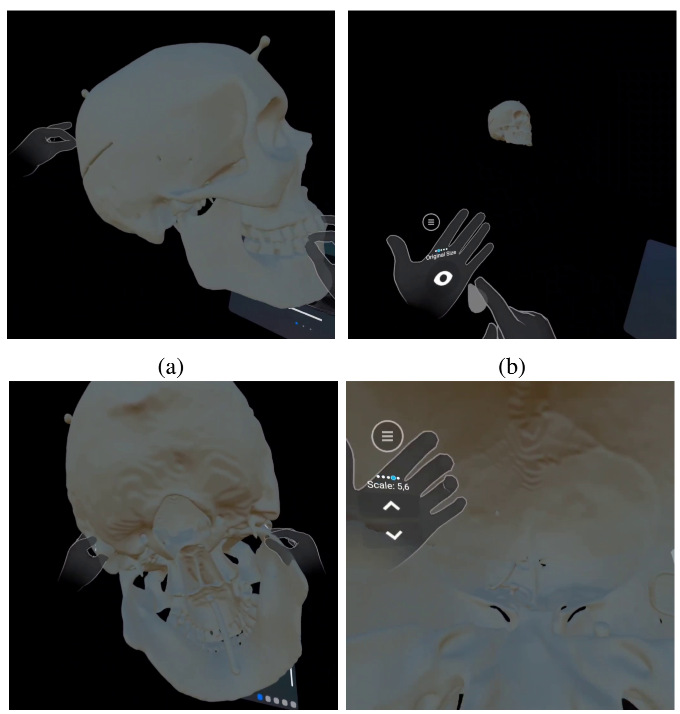
2) Hand Tracking and Interactive Features: The system's hand-tracking functionality enhances usability by enabling intuitive interactions with the 3D model (see Fig. 2). Using the Meta Software Development Kit (Meta SDK)'s hand-tracking capabilities [22], a customized menu was developed to allow users to perform actions like scaling and dragging directly through hand gestures. Increment and decrement buttons within the hand menu were tailored for operations such as adjusting the model size and manipulating its position. The simplicity of this approach ensured ease of use while leveraging the robust SDK features.

3) Synchronization of DICOM Updates and Red Plane Interactions: A critical technical component of the system is the synchronization between DICOM updates and the interactive red plane or slider functionality. The system divides the 3D volume into discrete slices based on the total number of DICOM images. By associating each slice with its corresponding spatial position, fine-tuning ensures accurate alignment.



(a) (b)

Fig. 1: (a) Example of a 2D DICOM image, and (b) the resulting 3D skull model generated using 3D Slicer.



(a) (b)

(c) (d)

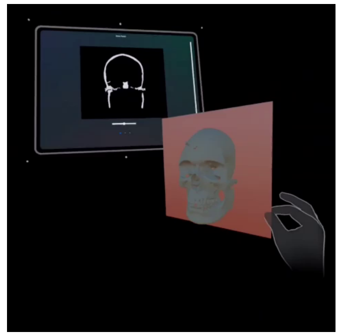
Fig. 2: Hand-tracking features: (a) Scaling. (b) Reset to the original scale. (c) Rotation. (d) Internal inspection of the 3D model.

B. XR diegetic user interface for visualization

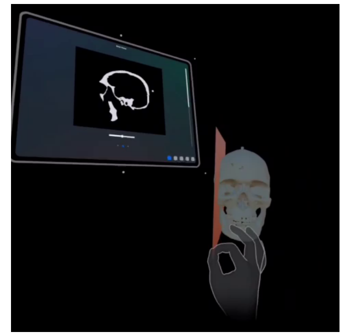
The visualization of both DICOM images and a 3D model of the skull is achieved through an advanced diegetic interface [32] integrated into the system which is inspired by the one provided by the neuronavigator [14]. The interface represents a virtual tablet with a virtual slider. The interface is designed to leverage hand-tracking technology, ensuring that interactions are as natural and intuitive as possible for the users. This design choice aims to provide a more immersive and user-friendly experience. In Fig. 3 we illustrate the use of the interface. Each image showcases the manipulation of a translucent red plane intersecting a 3D model of a skull, allowing users to view different cross-sectional images. In panel (a), the plane is moved along the z-axis, revealing a coronal section on the background screen. Panel (b) demonstrates sliding the plane along the x-axis, displaying a sagittal section. Panel (c) shows the plane moving along the y-axis, with an axial section appearing on the screen. A hand is seen interacting with the plane in each panel, emphasizing the user-friendly, intuitive interface. Additionally, users can utilize a slider to scroll through the DICOM images displayed on the panel, which simultaneously moves the red plane intersecting the 3D model, once the axis is selected. Both the slider and the red plane actions ensure that the appropriate DICOM image is loaded based on either the position of the section plane or the value selected on the slider, providing real-time updates to the visualization. In summary, the tablet interface for XR DICOM image visualization combines advanced UI elements with intuitive hand tracking and precise control mechanisms, offering users a robust and flexible tool for interacting with DICOM slice images. In this interface, the DICOM images are linked to the 3D model, enabling simultaneous visualization of the 3D model, corresponding DICOM slices, and the physical scanned object. This significantly enhances clinical workflows and provides an immersive, interactive experience for medical professionals.

C. Annotation system

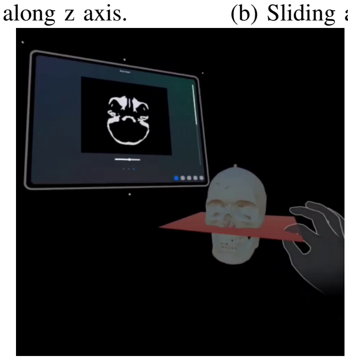
The system integrates an innovative feature that allows users to annotate DICOM images directly through controller-based inputs, enhancing the user's interaction with the medical data (see Fig. 4). This feature allows the annotation process to be intuitive, mimicking the natural action of marking critical areas using a brush-like tool. As the users interact with the virtual environment, they can highlight important features of the medical scans without having to rely on traditional mouse-and-keyboard setups or touchscreens. This direct interaction not only improves the precision and efficiency of the medical simulation but also maintains the immersion within the VR environment. In addition to this, annotations made on DICOM images will have an immediate effect on the 3D model generated from the scan data, creating a corresponding visual representation of the drawn annotations. This allows users to observe the impact of their annotations not only on the 2D DICOM images but also directly within the 3D model, ensuring a more comprehensive understanding of the spatial relationships and critical areas within the anatomy. This real-time feedback strengthens the interactive experience, enabling more precise annotations and facilitating deeper analysis of complex anatomical structures. Finally, the system enables users to save and load annotations made during their interaction with the DICOM images. This feature enhances the functionality by allowing users to revisit previous annotations, modify them, and integrate them into ongoing simulations or collaborative discussions with other



(a) Sliding along z axis.



(b) Sliding along x axis.



(c) Sliding along y axis.

Fig. 3: Example of DICOM images visualization sliding the red plane. As an alternative the user can move the slider in the panel to visualize the DICOM images.

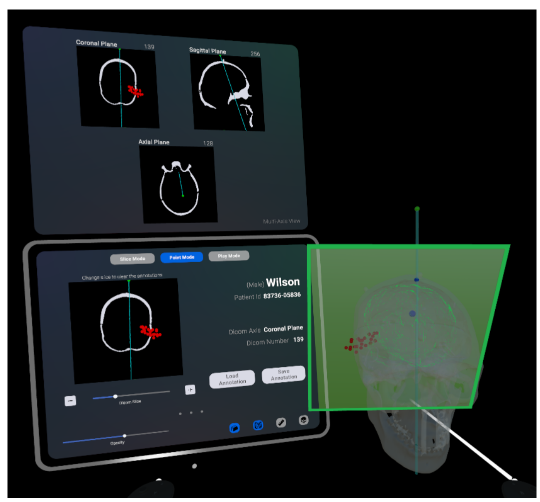


Fig. 4: DICOM annotations and direct visualization on the 3D model.

professionals. The ability to save and load annotations supports continuity in learning and analysis, as users can track their progress and refine their understanding over multiple sessions.

D. Underlying computational methods implemented for real-time rendering

To enhance system performance, several optimization strategies were implemented. To address performance constraints, the 3D model was optimized using Blender's Decimate modifier [5]. This process reduced the vertex count from 1,552,392 to 311,494, significantly decreasing file size from 163 MB to 40 MB. The optimized model retained sufficient visual fidelity for the system while ensuring smooth operation on standalone devices such as the Meta Quest 3. For image rendering, hardware acceleration was employed through the use of GPU processing, enabling real-time image manipulation while alleviating the CPU workload. Furthermore, the resolution was reduced from 2064×2208 (legacy headset resolution) to 1680×1768, maintaining visual fidelity while lowering the rendering demand. Additionally, the refresh rate was adjusted from 120 Hz (legacy headset refresh rate) to 72 Hz to ensure system stability during prolonged operation. These measures collectively contribute to real-time performance optimization by balancing computational efficiency and system reliability.

IV. Conclusions and Future Works

In this paper, we have described the integration of diegetic user interfaces within XR environments using Meta Quest 3 for the simultaneous visualization of DICOM images, 3D models, and physically scanned objects. Our approach aims to address the significant challenges associated with the loss of spatial context and cognitive load inherent in interpreting 2D DICOM images. By linking DICOM images to 3D models through an intuitive interface featuring a virtual tablet and slider controls, we have presented the prototype of a tool that can help clinicians enhance their workflow efficiency and accuracy. The ability to interact and manipulate 3D models in real-time, while viewing corresponding DICOM slices, represents a substantial advancement in medical visualization technology for medical education, pre-operative planning, and intra-operative guidance. Finally, our system incorporates an annotation feature for DICOM images, with annotations directly projected onto the 3D model. This integration fosters interactive, context-aware exploration and improves the understanding of complex medical data.

Future developments could focus on incorporating advanced simulation features. These enhancements may include integrating more realistic tissue properties and behaviors to provide lifelike feedback during the virtual experience. Additionally, multi-user collaboration features could be introduced, allowing multiple users to interact within the same virtual environment. This would facilitate real-time collaboration among clinicians, surgeons, trainees, and other medical staff, enabling them to discuss, plan, and practice medical procedures together, regardless of their physical locations. These features will allow users to visualize, practice, and plan complex medical procedures in a virtual environment, offering a risk-free and highly detailed platform for training and preparation.

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