IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 1 February 2024, accepted 25 February 2024, date of publication 11 March 2024, date of current version 1 April 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3375770

RESEARCH ARTICLE

A Framework to Enhance the Experience of CBCT Data in Real-Time Using Immersive Virtual Reality: Impacting Dental Pre-Surgical Planning

SHREENIDHI H. BHAT[1], K. S. HAREESHA[1], (Senior Member, IEEE), ABHAY T. KAMATH[2], ADARSH KUDVA[3], RAVINDRANATH VINEETHA[4], AND ANANYA NAIR[5]

[1]Department of Data Science and Computer Applications, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, Karnataka 576104, India
[2]Department of Dental Sciences, KMC Hospital, Mangaluru 575001, India
[3]Department of Oral and Maxillofacial Surgery, Manipal College of Dental Sciences Manipal, Manipal Academy of Higher Education, Manipal, Karnataka 576104, India
[4]Department of Oral Medicine and Radiology, Manipal College of Dental Sciences Manipal, Manipal Academy of Higher Education, Manipal, Karnataka 576104, India
[5]Department of Information and Communication Technology, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, Karnataka 576104, India

Corresponding author: K. S. Hareesha (hareesh.ks@manipal.edu)

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Institutional Ethics Committee, Kasturba Medical College, and Kasturba Hospital, Manipal, Karnataka, India, under Approval no. ECR/146/Inst/KA/2013/RR-19.

ABSTRACT Dental surgery has undergone a significant evolution with the advent of cone-beam computed tomography (CBCT), offering intricate 3D imagery vital for surgical planning, interventions, and diagnostics. Nonetheless, the comprehension of the extensive and intricate CBCT data remains a persistent challenge. To address this, virtual reality (VR) has emerged as a promising solution, empowering dental professionals to engage with CBCT data in real-time. This study introduces a VR framework meticulously designed for interactive and immersive visualization of CBCT data, enhancing the understanding of complex dental structures and pre-operative planning in dentistry. The proposed VR framework is developed by leveraging ray-marching volume rendering in the Unity platform with VR technologies for seamless interactions and to create an improvised immersive visualization environment. user-friendly interface supports intuitive CBCT volume manipulation through hand gestures and handheld controllers using an Oculus Quest 2 VR head-mounted device. A comprehensive evaluation involving 12 medical experts demonstrated the framework's effectiveness, with an impressive overall mean rating of 4.4 out of 5, emphasizing its favorable reception. Participants were awarded a mean score of 4.3 out of 5 for the VR experience and a remarkable 4.5 out of 5 for performance and interactions, highlighting its robustness. The high System Usability Scale (SUS) scores of 87% for VR experience and its impact and 91% for performance and interaction unequivocally indicate the exceptional acceptance of the Unity-based VR framework for CBCT image visualization among experienced medical experts. Therefore, this study illuminates how the proposed VR framework has the potential to revolutionize pre-surgical planning and decision-making processes in dental surgery, particularly in the realm of oral and maxillofacial surgery, promising improved patient outcomes.

INDEX TERMS Cone-beam computed tomography, virtual reality, volume rendering, GPU-based ray marching technique, immersive visualization, dental surgical planning.

The associate editor coordinating the review of this manuscript and approving it for publication was Lei Wei.

I. INTRODUCTION

Cone-beam Computed Tomography (CBCT) is a revolutionary imaging technique in dental surgery, providing essential

© 2024 The Authors. This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License.
For more information, see https://creativecommons.org/licenses/by-nc-nd/4.0/

3D images for surgical interventions, treatment planning, and diagnostics. While CBCT is highly effective in imaging hard tissue, it's intricate nature and voluminous data present significant challenges in visualization and interaction, limiting the optimal utilization of this invaluable asset [1]. Specifically, CBCT encounters difficulties in representing soft tissues with poor contrast and fails to capture the critical and sensitive aspects of a subject. In contrast, stereo-photogrammetry presents a viable solution by facilitating a three-dimensional recording of facial texture. This capability enables seamless integration with CBCT's three-dimensional surface image, effectively mitigating the identified limitations, as indicated in recent research findings [2].

To tackle these challenges, virtual reality (VR) emerges as a promising technology. It provides dental professionals with an immersive and interactive environment to visualize and manipulate CBCT data in real-time situations [3], [4]. Unlike simple 3D visualizations on 2D screens, VR allows users to virtually enter the 3D dataset within a simulated room, offering a unique and immersive experience. In VR, tactile hand controllers facilitate interaction, adding an extra layer of physical engagement with multi-dimensional virtual images. Clinicians can empower themselves with essential functions like zooming, translating, and rotating the volume dataset to orient, enlarge, and clarify data, offering unique perspectives in a clinical setting [5].

Despite the significant advantages of VR, its practical application in daily clinical use encounters challenges. VR systems must meet stringent requirements, including high performance, user-friendliness, and minimal data preprocessing, to seamlessly integrate into clinical practice [6]. Furthermore, the technique's feasibility for everyday clinical use is hindered by the limitation of many software programs to only support previously edited imaging datasets for AR/VR devices [7]. To overcome this challenge, there is a need for the development of a new imaging framework incorporating algorithms capable of simultaneously displaying diverse 3D datasets with an efficient feedback mechanism.

Our work focuses on bridging the gap between CBCT data and effective visualization in dentistry, utilizing VR technology to empower dental professionals in both practice and education. The main objectives of this paper include:

1) To develop a framework for integrating real-time CBCT data into an immersive VR environment.
2) Enabling real-time visualization and intuitive interaction with 3D reconstructions of dental anatomy using volume rendering techniques.
3) To evaluate the framework's usability and acceptance among dental professionals
4) Explore the potential benefits of immersive VR technology in enhancing the overall pre-operative planning of dental surgery.

II. LITERATURE REVIEW

Recent advancements in VR have brought exciting opportunities to medical imaging. One key area is the development of interactive visualization tools and realistic surgical simulators for enhanced pre-operative planning. Pires et al. [8] focused on integrating VR technology in medical imaging visualization, investigating highly realistic simulators and interactive medical data visualization stations for surgical planning. They also provided a list of software products that leverage VR for medical data visualization, including HoloDICOM [9], DICOM VR [10], and Precision VR [11].

Fortunately, researchers are optimizing traditional rendering algorithms like ray casting and texture-based methods through parallel computing and GPU acceleration, allowing for smoother and more efficient visualization of intricate anatomical structures. Additionally, initiatives like SlicerVR by Pinter et al. [12] are simplifying VR development by integrating VR functionalities into existing tools like 3D Slicer [13], making it easier to create VR scenarios for training, planning, and intervention guidance. Overall, these advancements suggest a promising future for VR in medical imaging, with the potential to revolutionize surgical planning and improve patient outcomes.

Traditionally, dental pre-surgical planning has relied heavily on static 2D and 3D CBCT visualizations, limiting interaction and potentially compromising surgical precision and patient understanding. However, a paradigm shift is underway with the emergence of immersive VR technology. VR offers real-time, interactive exploration of CBCT data in 3D, transforming how surgeons prepare for complex procedures. Recent research highlights the benefits of this advanced approach, demonstrating improved accuracy, enhanced communication with patients, and even reduced anxiety before surgery.

Leading the charge are innovative studies pushing the boundaries of VR capabilities in dentistry. Studies like Rocha et al. [14] demonstrate the potential of real-time VR frameworks for dental implant planning. These frameworks allow surgeons to manipulate CBCT data within VR, visualizing intricate anatomical structures with exceptional detail and facilitating precise implant placement in real time. This level of visualization goes beyond static 2D and 3D CBCT views, offering a dynamic and interactive experience for surgeons. Additionally, Kwon et al. [15] delve into the realm of sensory immersion by exploring the use of haptic feedback and spatial audio in VR simulations for dental students. This approach aims to enhance realism during training, providing tactile and auditory cues that mimic the real-world surgical environment. Emphasizing the broader educational and communication potential of VR in dentistry, Heo et al. [16] highlight how VR visualizations serve as a powerful tool for explaining complex procedures to patients. This enhances patient understanding and reduces anxiety before surgery.

Beyond research, game engines like Unity 3D are emerging as powerful tools for VR medical visualization. Their convenience, rapid development features, and platform abstraction capabilities make them ideal for building VR applications within healthcare. Integration tools like VtkToUnity [17] seamlessly bridge the gap between VTK, a popular medical visualization toolkit [18], and Unity [19], allowing developers to leverage their combined strengths. Unity's capabilities receive further validation through examples such as Koger et al.'s [20] immersive visualization of the cardiopulmonary system from CT scans. This demonstration showcases the potential of Unity in the medical VR landscape. Henceforth, VR promises a revolutionary leap in pre-surgical planning for dentists, allowing surgeons to explore 3D CBCT data in real time and make informed decisions before ever picking up a scalpel.

However, several challenges currently stand in the way of this technology reaching its full potential in everyday clinical practice. They are,

- Managing and processing intricate and voluminous CBCT datasets within VR environments while maintaining real-time performance poses hurdles [21], [22].
- Designing intuitive user interfaces is crucial to ensuring comfortable interaction with CBCT data in VR. Balancing simplicity with functionality is vital, allowing users to navigate and engage seamlessly with complex volumetric data without feeling overwhelmed or disoriented within the immersive VR environment [23].
- Many VR software programs only support pre-edited imaging datasets. This restriction disrupts the natural clinical workflow, as real-time data import and dynamic manipulation are essential for practical application [14].

Hence, to enhance decision-making, there is an urgent requirement for a comprehensive VR framework, enabling dentists and surgeons to navigate realistic and dynamic scenarios of oral anatomy.

To unlock VR's potential, a multidisciplinary approach is needed. Algorithmic advancements are crucial to reducing processing power while maintaining accuracy. User interface designers must prioritize intuitive interactions for navigating complex data without overwhelming users [24]. Finally, validation and optimization are essential to ensure rendered data fidelity and balance quality with real-time performance. Beyond these core challenges, practical considerations can enhance VR's clinical utility. Real-time data import, DICOM standardization for data exchange, and diverse data import capabilities will streamline workflows and enrich surgical planning [25].

In this study, we propose a VR framework to provide intuitive and immersive visualization of real-time CBCT data, promoting a better understanding of complex dental structures. The proposed methods include developing an optimized volume rendering algorithm within Unity's VR environment and prioritizing real-time rendering performance while upholding accuracy. Moreover, uniquely crafted interaction techniques, customizable and personalized for the Quest-2 VR headset, aspire to facilitate seamless manipulation and exploration of CBCT volume data. These techniques contribute to an improved user experience when navigating through anatomical structures. Lastly, this research endeavors to validate the effectiveness of the proposed VR framework for real-time CBCT data through comprehensive performance and usability assessments using objective metrics and user studies. The goal is to bridge the gap between intricate CBCT data and practical visualization for dental practitioners, fostering advancements in practice and education. This technological evolution promises to revolutionize the way dental professionals approach and execute surgical procedures.

III. MATERIALS AND METHODS

A. HARDWARE AND SOFTWARE USED

The main application is developed and tested on a Windows desktop computer with an Intel® CoreTM i7-8700K CPU processor, 32 GB of RAM, and Nvidia Titan RTX graphics. For a VR head-mounted device (HMD), we used a Meta Quest 2 advanced all-in-one VR headset. A developing and testing program is developed in C# and used Unity 2021.3.19f1 and Visual Studios 2019 for the VR application.

B. DATASET USED

In this work, we utilized two CBCT datasets acquired from the Manipal College of Dental Sciences, Manipal, India. The CBCT scans were reconstructed from dento-maxillofacial area CBCT scans, with a majority focusing on the mandible region (as shown in Figure 1). The imaging was performed using the i-CAT™ 17-19 Platinum Imaging System manufactured by Imaging Sciences International LLC, USA.

Both datasets had isotropic spatial resolution, with voxel spacings of 0.25mm x 0.25mm x 1.0mm, respectively. The size resolution of both datasets is 640 × 640 x 392 voxels. The gray values in the CBCT images are on the approximate Hounsfield unit (HU) scale, ranging from -1000 to 3095, providing a comprehensive representation of tissue density.

Prior to utilization, the acquired CBCT scans underwent pseudonymization to remove any identifiable patient information, ensuring compliance with privacy regulations and ethical standards.

C. METHODS

The Unity-based VR application framework presents a comprehensive approach to crafting immersive and interactive virtual reality experiences, with a primary focus on delivering a highly realistic and immersive environment for doctors. Leveraging detailed 3D representations from CBCT data, particularly dental structures, enhances the realism of virtual reality simulations. Through an optimized graphical pipeline, including efficient volume rendering, the framework preserves the visual quality of CBCT data. This emphasis on creating an optimal graphical pipeline is crucial for achieving realism, effective visualization, smooth interactivity, and user comfort. The framework's overall design aims to maximize the potential benefits of utilizing CBCT data, specifically in the context of dental pre-surgical planning.

The overall workflow of the Unity-based VR framework is shown in Figure 2. This methodology encompasses several

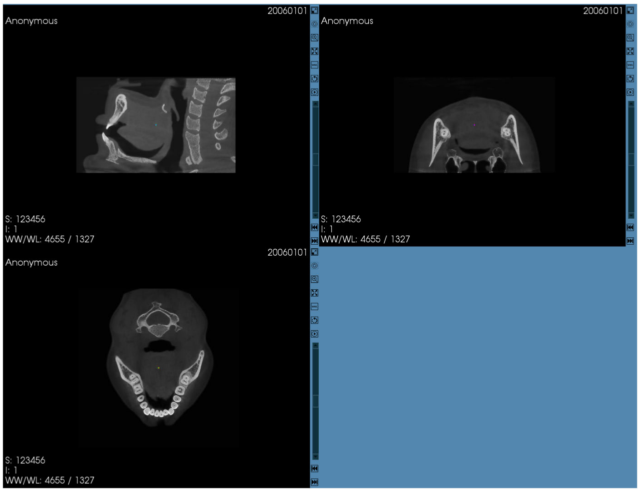


FIGURE 1. The CBCT scans depict the dento-maxillofacial area, with a predominant focus on the mandible region, as shown in axial, coronal, and sagittal views, respectively.

vital steps to ensure the successful development of a VR framework for CBCT visualization in dental surgery. They are:

1) Data Importing: In the data importation process, a specialized importer seamlessly integrates raw CBCT data formatted as DICOM files, containing intricate details of the oral and maxillofacial region. This importer is intricately designed to interface with Unity's Asset Importer APIs, allowing for the precise interpretation of DICOM files and image sequences. By performing tasks such as format conversion, metadata extraction, and voxel mapping, the importer ensures a faithful representation of anatomical structures within the VR scene. This process offers a precise and realistic portrayal of the patient's CBCT scans. This meticulous integration within Unity's framework is pivotal for creating an immersive and accurate virtual environment, especially crucial for surgical planning scenarios.
2) Scene Design and Asset Integration: In the process of scene design and asset integration, meticulous attention is given to crafting a virtual scene layout that mirrors a realistic surgical environment. This involves optimizing camera and lighting settings to enhance the overall visual experience. The overall Unity scene design involves the creation and integration of GameObjects, such as Camera Controller, Noise Manager, DICOM Manager, and File Browser Manager, to manage navigation, noise, DICOM data, and file-related operations, respectively. An integral facet of this process is the meticulous assignment of materials to volume-rendering components, significantly enhancing the achievement of visual realism. The efficient integration of 3D textures into the scenes is achieved by creating them from CBCT data, addressing considerations such as texture format determination, initialization, data normalization, and memory constraints. Additionally, the streamlined importation and organization of assets, particularly those associated with CBCT data, play a pivotal role in ensuring effective visualization. The comprehensive algorithms 1 & 2 include steps for camera control attachment, GameObject organization, asset integration, UI implementation, and 3D texture creation, collectively contributing to a fully immersive experience.
3) Volumetric Rendering & Visualization: The framework utilizes cutting-edge direct volume rendering techniques to achieve real-time visualization of CBCT data. It leverages the proposed GPU-based ray-marching algorithm (as shown in algorithm 3) for the interactive rendering of volumetric datasets. This sophisticated process involves the computation of color and opacity for each voxel along the ray, resulting in highly realistic and detailed visual representations of dental structures. The shader (elaborated in sectionIII-D3), designed to handle both forward and backward ray directions, takes into account visibility constraints, transfer functions, lighting calculations, and early ray termination for optimization. By skillfully mapping voxel values to color and opacity, the framework enhances visual representations, enabling the highlighting of specific anatomical structures or regions of interest. In essence, this approach ensures a seamless and immersive rendering experience, providing in-depth insights into dental structures during real-time interactions with CBCT data.
4) Interaction and User Interface Design: In this stage, the framework employs a range of interaction techniques to elevate user engagement and enhance the manipulation of CBCT visualization. Leveraging Unity's UI system, interactive elements like menus, buttons, and sliders are crafted to create a user-friendly experience. The framework facilitates operations such as creating and removing slicing planes, adjusting visualization parameters like visibility windows and zoom levels, and rotating the rendered volume. Moreover, it adeptly manages UI updates in response to user actions, ensuring a dynamic and responsive interface for CBCT manipulation. The incorporation of hand gestures enhances interaction, while controller inputs provide users with the ability to manipulate the visualization through rotation, zooming, and slicing actions. Gaze-based interaction is seamlessly integrated, enabling users to concentrate on specific regions of interest for a personalized and intuitive interactive experience.
5) Cross-Platform Deployment: The framework enables cross-platform deployment of the VR application to reach a wider audience. Unity supports major VR platforms such as Oculus Quest 2, HTC Vive, and other VR platforms. Developers can build and deploy the application on different devices and ensure accessibility and flexibility.

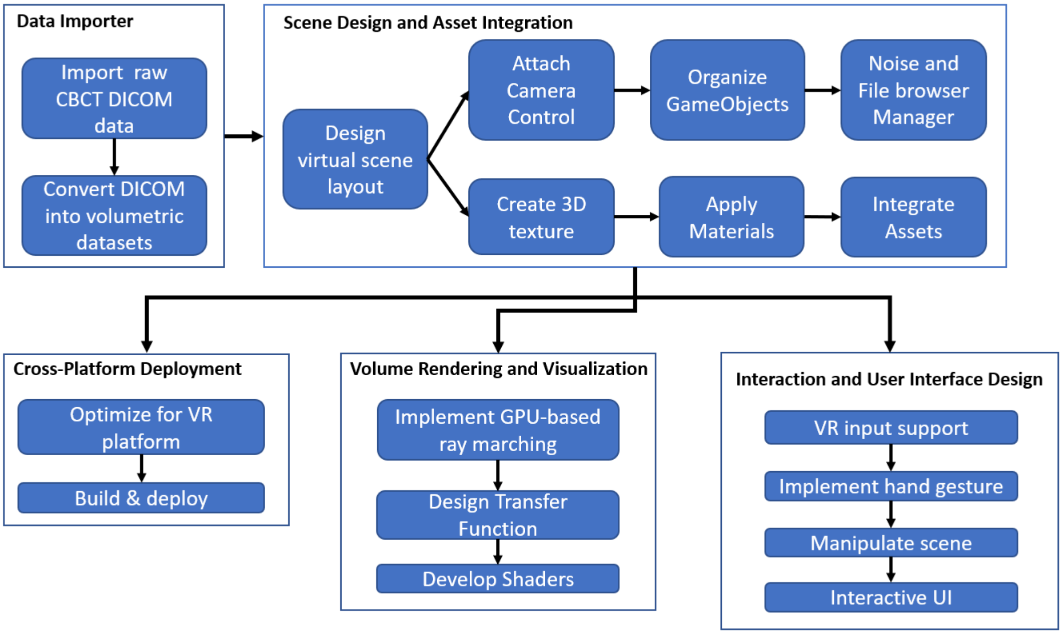


FIGURE 2. The overall workflow of the proposed Unity-based VR framework using Direct Volume Rendering for CBCT visualization in dental surgery.

D. ARCHITECTURE OF PROPOSED VR FRAMEWORK

The proposed Unity-based VR framework for CBCT visualization follows the Model-View-Controller (MVC) design pattern [26], ensuring a structured and modular approach to development (as shown in Figure 3). The Model-View-Controller (MVC) design pattern divides the Unity-based VR framework for CBCT visualization into three interconnected components: the Model, responsible for data management and rendering algorithms; the View, presenting data within the VR environment; and the Controller, managing user input and synchronizing interactions. Within this framework, the Model includes modules like the Data Importer for dataset handling and the Shader module for rendering techniques. The View comprises the VR Interface and VR View, enabling immersive visualization and interaction. The Controller coordinates user actions, updates the Model, and triggers rendering updates in the View, ensuring seamless communication between components and facilitating high-quality visualization and real-time interaction in the VR environment.

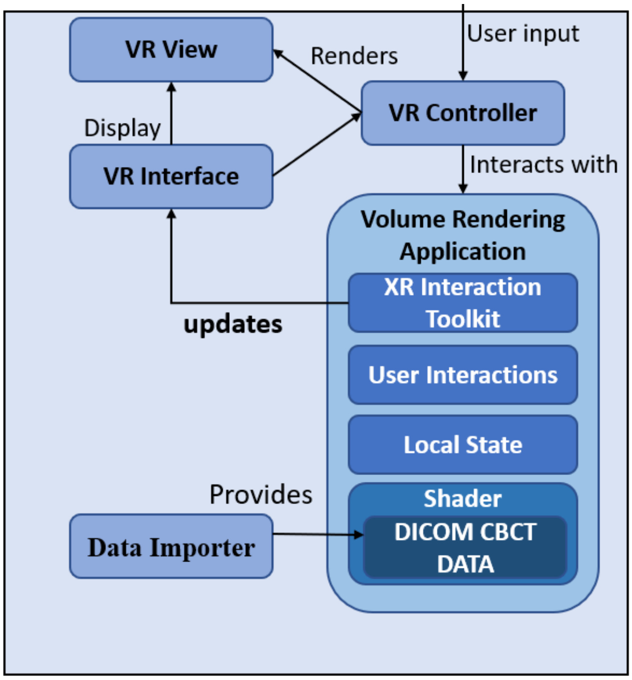


FIGURE 3. The Model-View-Controller (MVC) design pattern of the proposed Unity-based VR framework using Direct Volume Rendering for CBCT visualization.

1) DATA IMPORTER

An imported dataset has a dimension and a 3D pixel array. We downscale the data by averaging eight voxels per new voxel and replacing it with the original data. Then, create an importer for an image sequence dataset of the specified format for the use of DICOM and image sequence. Here we use importers like openDICOM [27] and SimpleITK [28]. Next, with the help of these importers, we define variables such as the DICOM directory path, material for rendering, image dimensions, and a texture 3D object for storing the volume data. Set up an Image Series reader to read the DICOM series and allocate an array to store the volume data based on width, height, and depth. Next, we create a texture 3D object with appropriate settings and assign it to the rendering material. Read the DICOM series slice by slice,

Algorithm 1 Camera Controller, Noise Manager, and File Browser Manager

```
function CAMERACONTROLLERUPDATE
    {Handle camera movement and rotation based on input}
    {Use Input.GetKey, Input.GetMouseButton, Input.GetAxis, etc.}
end function
function GENERATENOISETEXTURE(noiseDimX, noiseDimY)
    noiseTexture ← CREATEEMPTYTEXTURE(noiseDimX, noiseDimY)
    for $iY$ in range(noiseDimY) do
        for $iX$ in range(noiseDimX) do
            pixVal ← RANDOMRANGE(0.0, 1.0)
            noiseTexture[$iX$, $iY$] ← CREATECOLOR(pixVal, pixVal, pixVal)
        end for
    end for
    return noiseTexture
end function
function SHOWOPENFILEDIALOG(resultCallback, directory)
    dialogObject ← CREATEEMPTYGAMEOBJECT(“$_o$penFileDialog”) dialogComp ← dialogObject.ADDCOMPONENT(RuntimeFileBrowserComponent)

    dialogComp.dialogMode ← DialogMode.OpenFile
    dialogComp.callback ← resultCallback
    dialogComp.currentDirectory ← GETABSOLUTEDIRECTORYPATH(directory)
end function=0
```

converting each slice to a texture 2D object and copying the pixel data into a volume data array. Finally, perform the volume rendering technique using the volume data array and texture 3D object.

2) VOLUME RENDERING APPLICATION

The primary application is responsible for managing the system's state. It ensures the accurate loading of the data volume and sets up appropriate shaders. Additionally, it takes care of configuring the VR headset and controllers correctly, enabling users to interact seamlessly with the volume object. Currently, our volume rendering application supports various modes and features for users to interact with volume objects. They are:

1) File browser component: The file browser component enables the user to select the directory where the DICOM data is stored on the local system. It is implemented as a drop-down menu in the VR environment. The user can choose the appropriate file by navigating through the directory structure. Once the file is selected, an “OK” button is provided to load the data into the VR scene.

Algorithm 2 Creating 3D Texture From DICOM Data And Assigning Material to DICOM Data

```
function CREATE3DTEXTUREDATA(DICOMManager)
    Input: DICOMManager
    dicomData ← DICOMManager.GetDICOMData()
    voxelValues ← PROCESSDICOMDATA(dicomData)
    return voxelValues
end function
function CREATE3DTEXTURE(voxelValues)
    Input: voxelValues
    textureDimX, textureDimY, textureDimZ ← DETERMINETEXTUREDIMENSIONS(voxelValues)
    texture ← CREATEEMPTY3DTEXTURE(textureDimX, textureDimY, textureDimZ)
    for $x$ in range(textureDimX) do
        for $y$ in range(textureDimY) do
            for $z$ in range(textureDimZ) do
                texture[$x$, $y$, $z$] ← CONVERTVOXELVALUETOCOLOR(voxelValues[$x$, $y$, $z$])
            end for
        end for
    end for
    return texture
end function
function ASSIGNMATERIALTODICOMOBJECT(DICOMManager, material)
    Input: DICOMManager, material
     DICOMManager.AssignMaterial(material)
end function
function SETTEXTUREONMATERIAL(material, texture)
    Input: material, texture
    material.SetTexture(“MainTexture”, texture)
end function
function PROCESSDICOMDATA(dicomData) {Process DICOM data to obtain voxel values}
    Input: dicomData
    {Implement specific processing steps}
    return 3D array of voxel values
end function
 =0
```

2) Histogram Interface: The VR application incorporates a transfer function feature, allowing users to assign specific colors to different regions of the volume-rendered object [29]. A histogram interface is implemented, enabling users to define color mappings based on intensity values. This interactive feature allows users to customize the visualization of the object, facilitating better differentiation and highlighting of structures within the volume.

3) Interactions with the Volume-Rendered Object: The VR canvas provides a set of interactive options for users to manipulate the volume-rendered object. Implementation includes sliders for rotation along

Algorithm 3 Proposed Ray-Marching Algorithm

```
// Ray Setup
 Initialize ray, raymarchInfo, and lightDir
// Apply Jitter for Artifact Removal
 Jitter ray start position
// Initialize Color and Depth
 Initialize col and tDepth
// Ray Marching Loop
for $iStepin$[0, raymarchInfo.numSteps) do
    Compute current position along the ray
    // Perform Slice Culling
    if CROSS_SECTION_ON and IsCutout(currPos) then
        continue
    end if
    // Get Density/Sample Value
    density = getDensity(currPos);
    // Visibility Window Check
    if density $<$ _MinVal or density $>$ _MaxVal then
        continue
    end if
    // Calculate Gradient
    if TF2D_ON or LIGHTING_ON then
        Compute gradient
    end if
    // Apply Transfer Function
    if TF2D_ON then
        Compute color using 2D transfer function
    else
        Compute color using 1D transfer function
    end if
    // Apply Lighting
    if LIGHTING_ON and DVR_BACKWARD_ON then
        Apply lighting with backward ray
    else if LIGHTING_ON then
        Apply lighting with forward ray
    end if
    // Accumulate Color and Opacity
    if DVR_BACKWARD_ON then
        col.rgb = src.a $\times$ $src.rgb + (1.0f - src.a) \times col.rgb$;   $col.a = src.a + (1.0f - src.a) \times col.a$;

        # Optimized Early Ray Termination
        tDepth = max(tDepth, t $\times$ step(0.15, $src.a$)); else
        src.rgb src.a;
        col= (1.0f - $col.a$) $\times$ $src + col$;
        if col.a $>$ 0.15 and t $<$ tDepth then
            tDepth = t;
        end if
    end if
    // Early Ray Termination
    if not DVR_BACKWARD_ON and RAY_TERMINATE_ON and col.a $>$ OPACITY_THRESHOLD then
        break
    end if
end for=0
```

the x, y, and z axes, enabling users to adjust the orientation of the rendered object. Additionally, sliders for zooming in and out facilitate scaling operations, allowing users to zoom in or out on the object as desired.

4) Intensity Adjustment (Threshold): To enhance the visualization of the volume-rendered object, two sliders are implemented to control the maximum and minimum intensity functions. These sliders enable users to dynamically modify the intensity range displayed within the VR environment, offering flexibility in visualizing specific structures based on their preferences.
5) Slicing Plane: The application includes a button to create a slicing plane across any axis of the volume-rendered object. When the button is pressed, a 2D image of the sliced section is displayed on a canvas in front of the user. The user can interactively move the plane in any direction to view different sections of the object in a 2D format. Additionally, a button is provided to delete the slicing plane when it is no longer needed.

3) SHADER

The shader is the key component in the proposed framework, which plays a crucial role in implementing various functionalities. It handles basic volume rendering with ray marching and enables features such as slicing and volume highlighting [30].

For the basic direct volume rendering algorithm, the shader utilizes ray marching to cast rays through the volume, accumulating color and opacity values along the ray's path. It includes various features such as transfer functions, lighting, and early ray termination [22]. It begins by defining data structures to hold ray information and initializing ray marching parameters. The shader includes functions to calculate the view ray direction, intersect rays with an axis-aligned bounding box (AABB), and compute rays in different directions based on vertex position [26].

Utility functions facilitate color retrieval from transfer functions, density and gradient calculations, lighting direction determination, and lighting calculations. The vertex shader prepares the vertex output, while the main fragment shader implements the ray marching algorithm. It initializes ray parameters, applies a random offset for artifact reduction, and iteratively performs ray marching over a fixed number of steps. Slice culling is performed if cross-section mode is enabled.

During ray marching, the shader retrieves the density or sample value at each position within the volume. The transfer function 2D (TF2D) mode is active; it calculates the gradient at the current position and uses density and gradient magnitude to obtain color from the 2D transfer function [29]. Otherwise, it directly retrieves a color from the 1D transfer function. Lighting calculations are performed when enabled, considering the normalized gradient and the direction of the light source.

At each step, it retrieves the density value of the voxel at the current position and creates the *'src'* variable. This variable holds the *'RGB'* color values based on the density and an alpha value, likely representing opacity. The below equation ensures the appropriate weighting of voxel color and opacity contributions:

$$col.rgb = src.a * src.rgb + (1.0f - src.a) * col.rgb. \quad (1)$$

To accumulate color and opacity values along the ray's path, the shader blends the *'src'* color and opacity contribution with the accumulated *'col'* values. This blending uses linear interpolation *'lerp'*, ensuring proper transparency effects. To achieve this, a linear interpolation *'lerp'* is performed on the RGB values using the formula:

$$newRGB = lerp(oldRGB, currRGB, currAlpha). \quad (2)$$

The new alpha value is added to the old alpha multiplied by *(1 - new alpha)*.

The RGB components *'col.rgb'* are adjusted based on the alpha value *'src.a'*, while the alpha value *'col.a'* is updated to maintain the correct transparency level. Finally, the alpha value is updated as follows:

$$col.a = src.a + (1.0f - src.a) * col.a, \quad (3)$$

Through this iterative process, the shader refines the color and alpha values along the ray, resulting in a final composite image that accurately portrays the volumetric CBCT scan. This comprehensive visualization combines the colors and opacities of the encountered voxels, facilitating an adequate representation of the scanned volume with realistic color rendering and transparency effects.

If early ray termination is enabled, the shader checks if the accumulated opacity exceeds the threshold to terminate the loop early. Finally, the shader prepares the fragment output, including the color. If depth writing is enabled, the depth value is calculated based on the termination depth of the ray and the current position.

4) VR CONTROLLER STATE

It acts as the central controller of the application. It receives input from the VR interface and user interactions, such as selecting different rendering settings or navigating through the volume. To provide users with a realistic and immersive experience, the VR environment is designed as a dark surgery room with a spotlight focused on the volume-rendered object. Smooth movement is implemented to allow users to navigate within the virtual space. Users can use hand gestures or VR controllers to move freely around the environment, exploring the volume-rendered object from different angles and distances. The implementation ensures the movement is seamless and comfortable, enhancing the overall user experience. The VR Controller updates the volume rendering application and triggers appropriate actions based on user input.

In our VR-based framework, we have used hand tracking for object manipulation and interaction with volume instead of the Quest 2 controller. Utilizing hand-tracking capabilities, the VR application enables users to intuitively interact with the volume-rendered object. Users can utilize hand gestures to grab, rotate, and place objects in different positions within the VR environment. This feature enhances the immersive experience and facilitates more natural and intuitive object manipulation.

5) VR INTERFACE

- VR Hardware: Provides the necessary interfaces and functionalities to interact with the environment. For a VR head-mounted device (HMD), we used a Meta Quest 2 advanced all-in-one VR headset [31].
- VR Software: Provides the software layer for the VR experience. Our VR application is built on the Unity game engine platform with plugins provided by Oculus to integrate seamlessly with Oculus Quest 2 hardware. It includes libraries, scripts, and prefabs designed to support Oculus VR devices. Another package in Unity called the XR interaction toolkit simplifies the implementation of VR interactions [19]. It provides a set of components, utilities, and prefabs for common VR interactions like grabbing, teleportation, and object manipulation.

6) VR VIEW

It handles the rendering of the volume data in the VR environment. It receives updates from the controller and uses appropriate rendering techniques to display the volume on the VR interface. The VR view is responsible for rendering the volume from different perspectives and applying any necessary visual effects.

IV. RESULT ANALYSIS

A. VISUALIZATION OF CBCT IMAGES

We created a VR framework that supports CBCT images to build an interactive platform, elevating user engagement in dental surgical planning within an immersive 3D setting. This platform incorporates advanced hand-tracking features, allowing users to grab and manipulate anatomical structures interactively. It provides unique perspectives that go beyond what traditional visualization methods can offer.

To enable user-controlled movement within the VR environment, we've designed a virtual surgical room with spotlights for illumination (as shown in Figure 4). While in the VR space, users can utilize hand gestures, which offer hand-tracking capabilities as an alternative to VR controllers. Additionally, we've incorporated a file browser component, allowing users to select the relevant CBCT image from their system's file directory for rendering (as shown in Figure 5). To enhance image details, users can adjust optical properties like color and opacity using the histogram interface (as shown in Figure 6). Moreover, users have the flexibility to walk around, grab, and rotate the rendered images closely, enhancing their interactive experience within the VR environment.

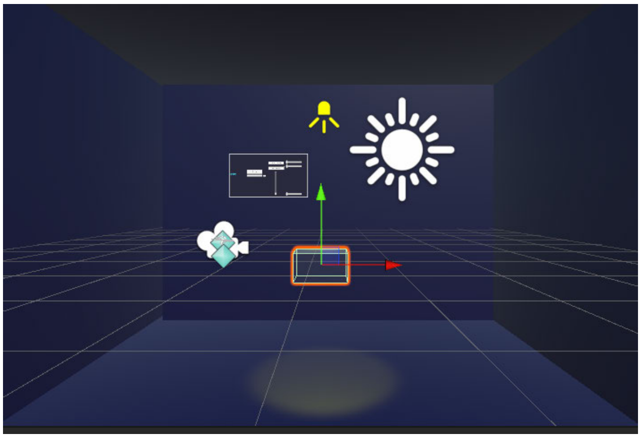


FIGURE 4. Realistic VR surgery room environment with a spotlight, directional light, and cameras on the volume-rendered object.

FIGURE 5. File browser component in a VR environment allows users to select DICOM data directories. The image showcases the file browser component, presented as a drop-down menu within the VR environment.

Furthermore, we've incorporated intensity adjustment features, allowing users to customize the intensity of the rendered images for enhanced visualization of specific anatomical structures, such as tissues within the volume, according to their preferences (as shown in Figure 7). Additionally, users can view a 2D image of the rendered volume by creating a slicing plane across any axis of the volume-rendered image, providing more detailed insights into the data (as shown in Figure 8).

Therefore, these interactive functions produce fresh viewpoints within the immersive 3D environment, improving user engagement in the analysis of patient data using CBCT models. They also provide essential information and create novel perspectives for medical visualization, ultimately influencing dental pre-operative surgical planning.

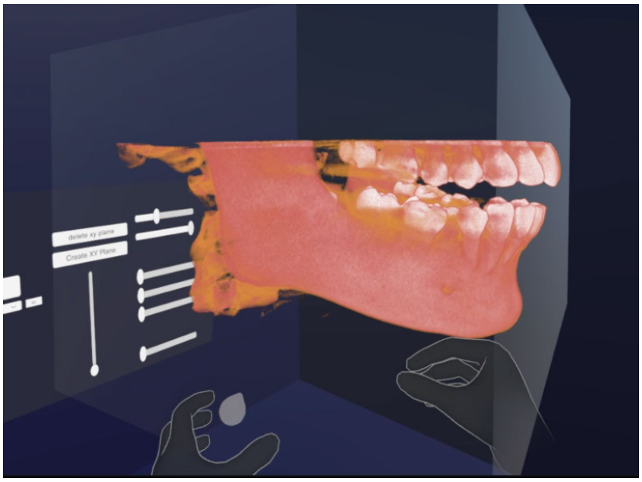


FIGURE 6. Interactive VR Framework with Transfer Function and Hand Tracking: The VR application offers transfer function and histogram interfaces, enabling users to customize volume-rendered objects by assigning colors based on intensity values. Additionally, users can manipulate the object through sliders for rotation and zooming, while benefiting from intuitive hand tracking for seamless and natural interactions within the virtual environment.

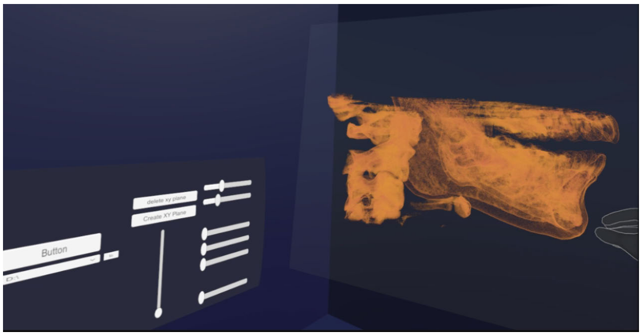


FIGURE 7. Customizable Intensity Adjustment: Users can fine-tune the intensity range of the volume-rendered object using intuitive sliders, allowing dynamic control over the visualization for better clarity and focus on specific structures within the VR environment.

B. ANALYSIS OF THE VR FRAMEWORK

Examining accuracy and precision directly within the context of a real-time immersive VR framework for dental surgery using CBCT, without ground truth, poses challenges due to the absence of a defined reference point. The immersive nature of VR, characterized by virtual representations, makes traditional verification methods inadequate. The challenges include the lack of a true baseline, potential distortions introduced during real-time VR rendering, and the subjective nature of visual assessment [32], [33]. To overcome these challenges, recent research papers commonly employ alternative methods such as expert evaluation and user experience assessment, effectively showcasing the VR model's realism and accuracy [34], [35].

In this study, we evaluated the efficiency of a VR framework based on Unity, focusing on the volume rendering

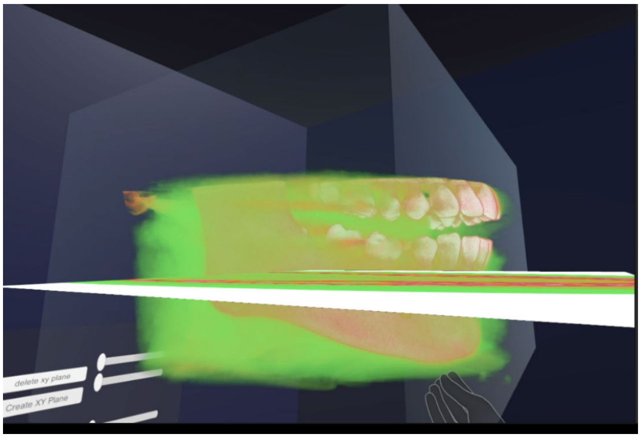


FIGURE 8. **Interactive Slicing Plane: Users can create a slicing plane and explore different cross-sectional views of the volume-rendered object in a 2D format.**

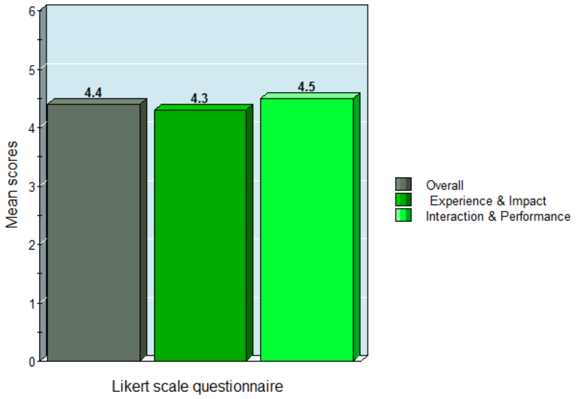


FIGURE 9. **Overall mean scores for the proposed Unity-based VR framework.**

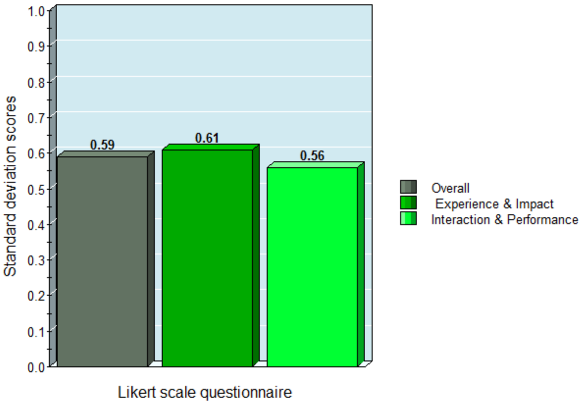


FIGURE 10. **Overall standard deviation scores for the proposed unity-based VR framework.**

of CBCT data for pre-surgical planning. The research involved 12 selected medical experts recognized for their expertise in the field, systematically assessing the realism and accuracy of anatomical representations of dental structures.

To ensure a comprehensive evaluation, we designed a well-structured Likert scale questionnaire [36], [37], addressing two core aspects: VR experience and its impact, and interaction and performance. Our goal was to gain valuable insights into how medical experts perceive the VR framework's capabilities and its potential implications for pre-surgical planning.

Analyzing the gathered data, we found an encouraging overall mean rating of 4.4 out of 5, with a relatively low standard deviation of 0.59. These results indicate that the medical experts had a highly positive experience with the Unity-based VR framework for CBCT data volume rendering. The VR environment proved effective in engaging users and providing an intuitive platform for pre-surgical planning needs.

Examining the first aspect, the VR experience and its impact, the participants' mean score of 4.3 out of 5 with a standard deviation of 0.61 reaffirms the framework's success in conveying information and creating a meaningful experience. Medical experts found the VR environment immersive and valuable for exploring CBCT data, potentially leading to improved visualization and a deeper understanding of anatomical structures before surgeries.

Regarding performance and interactions, the proposed Unity-based VR framework received an even higher mean score of 4.5 out of 5, with a standard deviation of 0.56. These results highlight the VR framework's robust performance in rendering CBCT data and enabling seamless interactions within the virtual environment. The VR framework's intuitive user interface and efficient interaction design garnered positive feedback, making it a valuable tool for pre-surgical planning processes. The overall mean scores and standard deviation scores for the proposed Unit-based VR framework is as shown in Figure 9 and Figure 10.

Additionally, the evaluation employed the "System Usability Scale" (SUS) [38], which involves assessing ten aspects related to system interaction, user experience, clinical impact, and performance, as well as user confidence in accepting or rejecting the framework, using 5-point Likert scales. The Likert scale ratings can be transformed into a score ranging from 0 to 100 using a formula [36]:

$$Percentage = (LikertScore/5) * 100 \tag{4}$$

with 100% indicating the highest level of applicability (0–50%: unacceptable, 51–67%: poor, 68%: okay; 69–80%: good, 81–100%: excellent).

The SUS scores of 87% for VR experience and its impact, and 91% for performance and interaction demonstrate the exceptional acceptance of the Unity-based VR framework for CBCT image visualization by experienced medical experts. The high VR experience and its impact score suggest that the framework offers a highly satisfactory and immersive user interface, reflecting its well-designed usability. The outstanding performance and interaction score indicate that the framework's responsiveness and functionality are excellent,

TABLE 1. Comparison of VR frameworks for medical image presentation and surgical planning.

Feature	Proposed VR Framework	SlicerVR	VTKUnity Plugin
Presentation Flexibility	Dynamic	Static	Static
Interaction Method	Hand Tracking System	HMD Movement	VR Controllers
User Convenience	High	Limited	Limited
Rotation, Slicing, and Manipulation	Seamless	Limited	Limited
Real-time Rendering Efficiency	Yes	No	No
Potential for Surgical Planning	High	Limited	Limited

making it efficient and effective for CBCT image-related tasks essential for pre-surgical planning. In summary, these SUS scores reflect the framework's widespread acceptance and appreciation among medical experts, highlighting its potential to significantly enhance CBCT image visualization in the context of pre-surgical planning.

Finally, our evaluation of the Unity-based VR application framework for CBCT data volume rendering in pre-surgical planning showcased highly positive experiences among medical experts. The immersive VR environment, coupled with efficient performance and interactions, holds promising potential for enhancing pre-operative visualization and decision-making processes. This study contributes valuable information to the growing research on VR applications in medical contexts, indicating the prospect of innovative technologies transforming pre-surgical planning and ultimately benefiting patient outcomes.

V. DISCUSSION

In dentistry, CBCT has emerged as a revolutionary imaging technique, providing detailed 3D images crucial for surgical interventions, treatment planning, and diagnostics. However, the abundance and intricate nature of CBCT data present obstacles to visualization and interaction, limiting its optimal utilization. To overcome these limitations, VR has emerged as a promising technology, offering an immersive and interactive environment for dental professionals to visualize and manipulate CBCT data in real-time.

The aforementioned statistics derived from the results demonstrate that medical experts had an exceptionally positive experience when using the Unity-based VR framework for an immersive experience of CBCT data in an interactive environment. It was observed that the VR environment effectively engaged users by conveying information and crafting a meaningful experience. Furthermore, medical experts regarded the VR environment as immersive and valuable for exploring CBCT data, potentially enhancing visualization, and promoting a deeper understanding of anatomical structures before surgical procedures. The outcomes underscored the VR framework's strong performance in rendering CBCT data and facilitating smooth interactions within the virtual environment.

The primary strength of the proposed Unity-based VR framework lies in its capacity for immersive visualization. Through VR, dental practitioners can engage with data on a profound level, exploring volumetric information from various perspectives and gaining deeper insights into intricate dental structures. This immersive experience results in more informed treatment decisions, surpassing the capabilities of conventional 2D or 3D representations.

The proposed framework has a better edge when compared with the existing VR frameworks like SlicerVR [12] and the VTKUnity plugin [17], which offer static presentations of medical images, our framework introduces dynamic flexibility (as shown in Table 1. These frameworks maintain fixed coordinate systems for medical images, akin to their presentation on desktops. While they do provide immersive 360-degree exploration, users must physically move around the images within the VR environment while wearing an HMD (Head-Mounted Display). This limitation disrupts the desired level of user interaction and convenience. However, in our innovative VR framework's environment, we've implemented a dynamic approach to presenting medical images within the VR space. Here, all functionalities, including rotation, slicing, and more, have been designed to be dynamic. This means users can interact with medical images seamlessly from their current position within the VR environment, resulting in a more immersive 360-degree experience.

Furthermore, to enhance the overall user experience and immersion, our proposed VR framework incorporates a hand-tracking system. Through intuitive hand gestures, users can perform all the required functionalities within the VR environment. This feature stands as a key strength of our study, significantly enhancing the user's ability to interact with and explore medical images. Dental professionals can rotate, zoom, slice, threshold, and manipulate the data at the user's convenience, making the application accessible to a wider range of users. This represents a significant departure from VR frameworks and applications provided by SlicerVR and plugins like VTKUnity, which rely on VR controllers for interactions.

Additionally, we achieve real-time volume rendering efficiently through GPU-based ray marching algorithms within Unity. This technology enables smooth and dynamic interaction during surgical planning and diagnostics, making our application highly practical and suitable for clinical purposes.

Lastly, the validation studies conducted in this research further enhance the credibility and value of the work. Notably, this research lays the foundation for the potential application of VR experiences to other surgical procedures within the oral and maxillofacial regions, showcasing the transformative potential of innovative technologies in pre-surgical planning.

Despite its strengths, the proposed system faces challenges in handling large CBCT datasets efficiently. Further optimizations may be needed for the real-time rendering of voluminous data. Furthermore, integrating advanced visualization techniques could enhance the system's effectiveness. This would enable the highlighting of specific anatomical regions, conducting surgical simulations, and superimposing virtual objects onto CBCT data for improved pre-surgical planning and training.

Overall, the proposed Unity-based VR framework offers an immersive and efficient solution to visualize and interact with CBCT data, empowering dental professionals to make more informed decisions and enhancing the quality of dental treatments.

VI. CONCLUSION

In conclusion, the Unity-based VR framework for CBCT data in dentistry offers significant benefits and potential for improving surgical interventions, treatment planning, and diagnostics. By leveraging VR technology and real-time volume rendering, dental professionals can immerse themselves in the data, gaining valuable insights and a better understanding of complex dental structures. The user-friendly interface, with support for hand gestures instead of handheld controllers, enhances the interaction experience, making it accessible and intuitive for a wider range of users.

The application's success is evident from the positive feedback received during the evaluation phase, where medical experts commended its immersive experience, visualization capabilities, and efficient interactions. The VR environment proved to be an effective platform for exploring CBCT data, potentially leading to improved pre-surgical planning and decision-making processes.

However, some challenges need to be addressed. Handling large CBCT datasets efficiently remains a concern, and further optimizations may be required to ensure the smooth rendering of voluminous data. Additionally, incorporating advanced visualization techniques, such as highlighting specific anatomical regions and simulating surgical procedures, could further enhance the application's effectiveness.

Despite these challenges, the Unity-based VR application demonstrates great promise in transforming dental pre-surgical planning and diagnostics. With continuous improvements and enhancements, it has the potential to become an invaluable tool for dental professionals, ultimately benefiting patient outcomes and advancing the field of dentistry.

ACKNOWLEDGMENT

The authors express their gratitude to the entire Oral and Maxillofacial Department, Manipal College of Dental Sciences, for actively participating in the validation study and for their valuable insights and suggestions, which have significantly contributed to the enhancement of their proposed VR application framework. Special thanks are extended to the Department of Oral Medicine and Radiology, for their invaluable assistance in providing the pseudonymized CBCT data.

ETHICAL APPROVAL

Ethical approval for this study was obtained from the Institutional Ethics Committee, Kasturba Medical College, and Kasturba Hospital, Manipal, Karnataka, India. (Approval number ECR/146/Inst/KA/2013/RR-19)

CONFLICT OF INTEREST

The authors have no conflict of interest.

ARTIFICIAL INTELLIGENCE DISCLOSURE

To improve the readability and quality of language, all parts of this paper have been grammatically revised using the tool CHATGPT. After using this tool/service, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

REFERENCES

[1] C. Angelopoulos, W. C. Scarfe, and A. G. Farman, "A comparison of maxillofacial CBCT and medical CT," *Atlas Oral Maxillofacial Surgery Clinics*, vol. 20, no. 1, pp. 1–17, Mar. 2012.

[2] O. de Waard, F. Baan, L. Verhamme, H. Breuning, A. M. Kuijpers-Jagtman, and T. Maal, "A novel method for fusion of intra-oral scans and cone-beam computed tomography scans for orthognathic surgery planning," *J. Cranio-Maxillofacial Surgery*, vol. 44, no. 2, pp. 160–166, Feb. 2016.

[3] A. S. Pillai and P. S. Mathew, "Impact of virtual reality in healthcare: A review," *Virtual and Augmented Reality in Mental Health Treatment*, 2019, pp. 17–31.

[4] F. King, J. Jayender, S. K. Bhagavatula, P. B. Shyn, S. Pieper, T. Kapur, A. Lasso, and G. Fichtinger, "An immersive virtual reality environment for diagnostic imaging," *J. Med. Robot. Res.*, vol. 1, no. 1, Mar. 2016, Art. no. 1640003.

[5] A. Ayoub and Y. Pulijala, "The application of virtual reality and augmented reality in oral & maxillofacial surgery," *BMC Oral Health*, vol. 19, pp. 1–8, Dec. 2019.

[6] A. J. Lungu, W. Swinkels, L. Claesen, P. Tu, J. Egger, and X. Chen, "A review on the applications of virtual reality, augmented reality and mixed reality in surgical simulation: An extension to different kinds of surgery," *Exp. Rev. Med. Devices*, vol. 18, no. 1, pp. 47–62, Jan. 2021.

[7] S. G. Izard, J. A. J. Méndez, P. Ruisoto, and F. J. García-Peñalvo, "NextMed: How to enhance 3D radiological images with augmented and virtual reality," in *Proc. 6th Int. Conf. Technol. Ecosystems Enhancing Multiculturality*, 2018, pp. 397–404.

[8] F. Pires, C. Costa, and P. Dias, "On the use of virtual reality for medical imaging visualization," *J. Digit. Imag.*, vol. 34, no. 4, pp. 1034–1048, Aug. 2021.

[9] *Holodicom*. Accessed: Aug. 2023. [Online]. Available: http://www.holodicom.com/

[10] C. Williams and K. Kovtun. *Dicom VR: Visualizing and Manipulating Medical Imaging in a New Dimension*. Accessed: Aug. 2023. [Online]. Available: http://info@precisionostech.com/

[11] P. A. Foundation. *Precisionos: Delivering on the Promise and Potential of Virtual Reality Training*. Accessed: Aug. 2023. [Online]. Available: http://info@precisionostech.com/

[12] C. Pinter, A. Lasso, S. Choueib, M. Asselin, J.-C. Fillion-Robin, J.-B. Vimort, K. Martin, M. A. Jolley, and G. Fichtinger, "SlicerVR for medical intervention training and planning in immersive virtual reality," *IEEE Trans. Med. Robot. Bionics*, vol. 2, no. 2, pp. 108–117, May 2020.

[13] S. Pieper, M. Halle, and R. Kikinis, "3D slicer," in *Proc. 2nd IEEE Int. Symp. Biomed. Imag., Macro Nano*, Apr. 2004, pp. 632–635.

[14] A. V. Rocha, A. O. Pereira, P. J. Vieira, C. H. Borges, P. J. Correia, M. H. Magalhaes, V. H. Queiroga, and A. Rocha, "A real-time volumetric rendering framework for VR-assisted dental implant planning," *J. Med. Dental Sci.*, vol. 12, no. 2, pp. 35–42, 2023.

[15] S. Kwon, S. Kim, S. Jo, S. Jung, J. Lee, J. Lee, J. Choi, and H. Kim, "Development and evaluation of a virtual reality dental simulator using haptic feedback for dental students," *Int. J. Hum.-Comput. Interact.*, vol. 38, no. 12, pp. 1025–1044, 2022.

[16] J.-H. Heo, M.-S. Lee, H.-I. Kim, and S.-I. Jung, "Immersive virtual reality simulation for dental education and training: A review," *Virtual Reality*, vol. 25, no. 3, pp. 483–497, 2021.

[17] G. Wheeler, S. Deng, N. Toussaint, K. Pushparajah, J. A. Schnabel, J. M. Simpson, and A. Gomez, "Virtual interaction and visualisation of 3D medical imaging data with VTK and unity," *Healthcare Technol. Lett.*, vol. 5, no. 5, pp. 148–153, Oct. 2018.

[18] P. O'Leary, S. Jhaveri, A. Chaudhary, W. Sherman, K. Martin, D. Lonie, E. Whiting, J. Money, and S. McKenzie, "Enhancements to VTK enabling scientific visualization in immersive environments," in *Proc. IEEE Virtual Reality (VR)*, Mar. 2017, pp. 186–194.

[19] Unity Technologies. *Unity XR Interaction Toolkit*. [Online]. Available: https://unity.com/unity-xr-toolkit

[20] C. R. Koger, S. S. Hassan, J. Yuan, and Y. Ding, "Virtual reality for interactive medical analysis," *Frontiers Virtual Reality*, vol. 3, Feb. 2022, Art. no. 782854.

[21] J. Sutherland, J. Belec, A. Sheikh, L. Chepelev, W. Althobaity, B. J. W. Chow, D. Mitsouras, A. Christensen, F. J. Rybicki, and D. J. La Russa, "Applying modern virtual and augmented reality technologies to medical images and models," *J. Digit. Imag.*, vol. 32, no. 1, pp. 38–53, Feb. 2019.

[22] S. A. El-Seoud, A. Mady, and E. Rashed, "An interactive mixed reality ray tracing rendering mobile application of medical data in minimally invasive surgeries," Tech. Rep., 2019.

[23] T. Joda, G. O. Gallucci, D. Wismeijer, and N. U. Zitzmann, "Augmented and virtual reality in dental medicine: A systematic review," *Comput. Biol. Med.*, vol. 108, pp. 93–100, May 2019.

[24] J. Fons, E. M. Lahoya, P. P. V. Alcocer, and I. N. Alvaro, "Rendering and interacting with volume models in inmmersive environments," in *Proc. 28th Spanish Comput. Graph. Conf.*, Madrid, Spain, Jun. 2018, pp. 47–50.

[25] A. K. Bartella, M. Kamal, I. Scholl, S. Schiffer, J. Steegmann, D. Ketelsen, F. Hölzle, and B. Lethaus, "Virtual reality in preoperative imaging in maxillofacial surgery: Implementation of 'the next level?"' *Brit. J. Oral Maxillofacial Surg.*, vol. 57, no. 7, pp. 644–648, Sep. 2019.

[26] Mattatz. (Nov. 2018). *Unity-Volum-Rendering*. Accessed: Feb. 25, 2020. [Online]. Available: https://github.com/mattatz/unity-volume-rendering

[27] OpenDICOM, *OpenDICOM: High Performance DICOM Library*. [Online]. Available: https://www.opendicom.org

[28] B. C. Lowekamp, D. T. Chen, L. Ibáñez, and D. Blezek, "The design of SimpleITK," *Frontiers Neuroinform.*, vol. 7, p. 45, Dec. 2013.

[29] S. H. Bhat, K. S. Hareesha, A. T. Kamath, A. Kudva, and H. Shashank, "Interactive volume rendering module using two-dimensional transfer function on cone-beam computed tomography data," in *Proc. 10th Int. Conf. Signal Process. Integr. Netw. (SPIN)*, Mar. 2023, pp. 761–766.

[30] N. D. Duong, X. Liang, and J. Tian, "VR volume rendering," Tech. Rep.

[31] *Oculus Quest*. [Online]. Available: http://www.oculus.com/quest/

[32] N. J. Kelly, J. Hallam, and S. Bignell, "Using interpretative phenomenological analysis to gain a qualitative understanding of presence in virtual reality," *Virtual Reality*, vol. 27, no. 2, pp. 1173–1185, Jun. 2023.

[33] J. H. D. Menck, H. Lechte, M. Riedel, J. H. C. Jaja, and J. Tümler, "Realism and experiments: Investigating virtual reality experiments," Tech. Rep., 2023.

[34] Y. Pulijala, M. Ma, M. Pears, D. Peebles, and A. Ayoub, "Effectiveness of immersive virtual reality in surgical training-a randomized control trial," *J. Oral Maxillofacial Surg.*, vol. 76, no. 5, pp. 1065–1072, 2018.

[35] G. Hattab, A. Hatzipanayioti, A. Klimova, M. Pfeiffer, P. Klausing, M. Breucha, F. V. Bechtolsheim, J. R. Helmert, J. Weitz, S. Pannasch, and S. Speidel, "Investigating the utility of VR for spatial understanding in surgical planning: Evaluation of head-mounted to desktop display," *Sci. Rep.*, vol. 11, no. 1, p. 13440, Jun. 2021.

[36] J. Jerald, *The VR Book: Human-Centered Design for Virtual Reality*. Morgan & Claypool, 2015.

[37] Y. Pulijala, M. Ma, M. Pears, D. Peebles, and A. Ayoub, "An innovative virtual reality training tool for orthognathic surgery," *Int. J. Oral Maxillofacial Surg.*, vol. 47, no. 9, pp. 1199–1205, Sep. 2018.

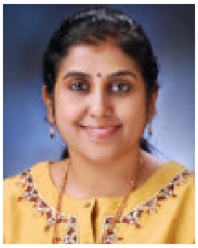
[38] S. Borsci, S. Federici, and M. Lauriola, "On the dimensionality of the system usability scale: A test of alternative measurement models," *Cognit. Process.*, vol. 10, no. 3, pp. 193–197, Aug. 2009.

SHREENIDHI H. BHAT received the B.E. degree in computer science and engineering from Visvesvararya Technological University, Belgavi, Karnataka, India, in 2016, and the M.Tech. degree in software engineering from Manipal Academy of Higher Education, Manipal, India, in 2018, where he is currently pursuing the Ph.D. degree with the Department of Data Science and Computer Applications, Manipal Institute of Technology, under the Dr. T. M. A. Pai (full-time) Ph.D. Scholarship. His research interests include 3D computer graphics, medical image processing and visualization, and virtual reality.

K. S. HAREESHA (Senior Member, IEEE) has been with Manipal Institute of Technology, MAHE, since 2008, where he is currently a Professor with the Department of Data Science and Computer Applications. He is also the Co-Founder of a start-up company Kumudha Health Tech. Pvt. Ltd., a spin-off of MAHE incubated in MUTBI. He has 22 years of teaching experience. His research interests include machine learning algorithms and understanding and designing intelligent soft computing models in digital image processing and VR and AR applications. In this area, he has published 46 peer-reviewed research articles in reputed international journals indexed by Scopus and WoS. He has given numerous invited talks and tutorials. He is a recognized guide at MAHE and so far he has guided six Ph.D. students. He is supervising three Ph.D. research scholars. He has filed two patents in his research domain. He has been a technical committee member of many international conferences in India and abroad. He is a Senior Member of MISTE and IACSIT. He has received fellowship awards from the National Science Foundation, USA, and the Federation University, Australia, and MAHE, Manipal, for his research contributions. He is a Reviewer for the *Journal of the International Measurement Confederation* (Elsevier), *Peer-to-Peer Networking and Applications* Journal, and *Computer Methods and Programs in Biomedicine* Journal.

ABHAY T. KAMATH is currently practicing as the Chief Consultant and the Head of Department with the KMC Hospital, Mangaluru. He has been the former HOD with the Department of OMFS, MCODS, Manipal. He is a Faculty Member of AOCMF, India, and one of the Indian Society of TMJ Surgeons founder members. He was a Panelist from India for the AO Davos Course in Condylar Fractures in Switzerland, in 2018. He procured fellowships in TMJ replacement, orthognathic surgery, and trauma in Canada, Australia, and Swansea. He received advanced training in TMJ surgeries in Jacksonville Atlanta. He is a Reviewer of the *Indian Journal of Oral and Maxillofacial Surgery*.

ADARSH KUDVA is currently an Associate Professor with the Department of Oral and Maxillofacial Surgery, Manipal College of Dental Sciences, Manipal Academy of Higher Education, Manipal. He has received memberships in oral and maxillofacial surgery from The Royal College of Surgeons of Edinburgh and a fellow of the International Board for the Certification of Specialists in Oral and Maxillofacial Surgery. He also procured fellowships in plastic and reconstructive microsurgery from the Chang Gung Memorial Hospital, Taiwan; and in head and neck surgery from the Rajiv Gandhi University of Health Sciences, India. He has published nearly 40 peer-reviewed research articles in reputed national and international journals indexed by Scopus and WoS. He has given numerous invited lectures and also has two patents in his research domain.



RAVINDRANATH VINEETHA has a teaching experience of more than 16 years. She is currently a Professor and the Head of the Department of Oral Medicine and Radiology, Manipal College of Dental Sciences, Manipal. She has more than 55 peer-reviewed publications in Scopus-indexed journals. Her research interests include conebeam CT applications and oral mucosal lesions in systemic disorders. She was a recipient of the MAHE-Faimer International Fellowship (MFILIIPE) in interprofessional practice and education. She has undertaken various interdisciplinary projects on radiologic applications and artificial intelligence. She has been a Reviewer of *BMJ Oral Health*, the *Indian Journal of Medical Research*, and the *Indian Journal of Academy of Oral Medicine and Radiology*.

ANANYA NAIR is currently pursuing the B.Tech. degree in information technology with the Department of Information and Communication Technology, Manipal Institute of Technology, Manipal. Her research interests include domains of virtual reality and human–computer interaction.

• • •