An Efficient System for 3D Reconstruction, Segmentation, and Visualization of DICOM Medical Images for Virtual and Augmented Reality Environments

K. H. Balhaf (1,*)
A. K. Al-Majhali (2)
N. A. Munassar (1)
A. Bin Sheikh Abubakr (2)
M. R. Al-Nasser (2)
N. H. Al-Fakih (2)
A. Swailem (2)

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[1] Department of Computer Science College of Applied and Health Sciences, Mahrah University, Mahrah, Yemen.
[2] Information Technology Department, College of Engineering and Computing, University of Science and Technology, Aden, Yemen.
*Corresponding Author's Email: khaledbalhaf2021@gmail.com

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Khaled Hassan Balhaf
Department of Computer Science College of Applied and Health Sciences , Mahrah University, Mahrah, Yemen.
Information Technology Department, College of Engineering and Computing, University of Science and Technology, Aden, Yemen.
khaledbalhaf2021@gmail.com

Abdulrahman Bin Sheikh Abubakr
Department of Computer Science,
College of Applied and Health Sciences,
Mahrah University, Mahrah, Yemen.
Dahoomaladej@gmail.com

Adnan Swailem
Department of Computer Science,
College of Applied and Health Sciences,
Mahrah University, Mahrah, Yemen.
a.baadil@mhru.edu.ye

Ahmed Khaled Al-Majhali
Department of Computer Science,
College of Applied and Health Sciences,
Mahrah University, Mahrah, Yemen.
ahmed774425007@gmail.com

Mahmood Riyadh Al-Nasser
Department of Computer Science,
College of Applied and Health Sciences,
Mahrah University, Mahrah, Yemen.
mhmodalnaser25@gmail.com

Nabil Ali Munassar
Information Technology Department,
College of Engineering and Computing,
University of Science and Technology,
Aden, Yemen.
N.munassar@ust.edu

NoorAldeen Hamood Al-Fakih
Department of Computer Science,
College of Applied and Health Sciences,
Mahrah University, Mahrah, Yemen.
nooraldennalfiqeh@gmail.com

Abstract— This study used a scalable approach to convert DICOM medical files into interactive 3D models. Suitable for advanced visualization and extended reality applications. To extract metadata, we use a pydicom library; we also used the NumPy and PyVista libraries for creating images. The suggested solution uses genuine DICOM datasets that were collected from Al-Ghaydah Central Hospital. CT and MRI slices are put together into a volumetric representation after being preprocessed. Then, the Marching Cubes technique is used to recover the surface. Then, connectivity-based mesh segmentation is used to make three-dimensional visualization accurate and interactive. As a preprocessing step, the contrast and sharpness filters showed better visibility of the structures, and the segmentation provided well-recognized anatomical separation. Reconstruction times were held within reasonable limits (1-5 seconds, depending on the size and quality of the dataset), and GUI responsiveness was also maintained throughout the entire procedure. The system's ability to produce complex models from real clinical data underscores its value in medical education, simulation, and research.

Keywords—Medical Images, Augmented Reality, Visualization , 3D Reconstruction, Segmentation.

I. INTRODUCTION

The world in recent decades has seen a rapid technological revolution that has significantly changed human life. One of the most important aspects of this transformation is the introduction of the Virtual Reality (VR) and the Augmented Reality (AR) technology, which transforms the interaction between humans and machines. Possibilities in education, industry, medicine, and entertainment, as well as training, have been broadened by these technologies, which provide interactive digital space that simulates or adds to reality by providing additional information [1]. Virtual reality is a technology that enables users to completely surround themselves in the computer-generated 3D world, providing the feeling that they are in another world and can move around and interact using a special headgear and motion sensors [2].

Augmented reality, on the other hand, is a combination of both the physical and virtual elements that involve overlaying digital layers of images, text, or 3D models onto the real world to enhance the experience and the level of interactivity [3].

This project is aimed at showing medical images and transforming DICOM files into virtual reality and augmented reality environments. This enables the physicians and researchers to see the anatomical and functional complexity of the human body in real-time 3D. Such an approach improved the accuracy of diagnosis, advanced the training of medical practices, and gave a better understanding of interior structures that are difficult to visualize in traditional two-dimensional imaging [4]. This research utilized different augmented reality interaction features on real data and photos collected at the Al-Ghaydah Central Hospital. The latter section presents a list of related articles, and the third part describes our method used in this study. The fourth and fifth sections outline and interpret the research findings. Finlay, in section six, closes with the review of our research and future projects.

II. RELATED WORK

There are many studies that explored different ways of processing, converting, and displaying DICOM data, each with a specific emphasis on one aspect of medical 3D modeling and image management. The segment-anyway model was modified to a 3D structure allowing automated segmentation with radiation field data, which was introduced by Cen et al. [5] and presented the SA3D methodology. Where they focus on automated segmentation through AI models, our work focuses on the interactive viewing and editing of 3D models. Badea et al. [6] used DICOM files to design 3D-printed physical models to be used in the quantification of medical radiation. Although both of these studies used DICOM data, the goal of our study is different as it limits itself to the visual and interactive display as opposed to the creation of the actual physical models.

The authors in [7] created a simplified system of converting DICOM data into STL models by external software, such as 3D Slicer and Ultimaker Cura. On the other hand, our solution introduces an independent Python programming language, which converts and visualizes DICOM models without using external software.

Sullivan and Kaszynski [8] introduced the PyVista library on the software implementation level to support effective 3D displaying, analysis, and mesh processing, which is the same library that we used in our research to render the model and manipulate it. These capabilities were then improved by Bane Sullivan et al. [9] to include advanced mesh processing and visualization features. The software tools used to make STL models from files in DICOM format were assessed by Kamio et al. [10]; however, our project augments this idea by providing real-time interactive model manipulation within a single environment.

Mathes and Drakopoulos [11] discussed the problem of shearing and surface smoothing with regard to the 3D surface and geometry involved that could be useful in improving the segmentation and rendering phases of our system. Wailly [12] proposed a hidden-line elimination new method for 3D model techniques that might be used to increase the quality of rendering in the next stage, and Bridge et al. studied the highdicom library, which manages annotations and information in X-ray files [13] [14]. Though our project is not supported by the use of annotation tools, the reason why we are doing so is the same, which is to increase the efficiency of DICOM data interpretation and visualization. The study by Liu et al. [15] explored methods to optimize PACS storage performance; however, although they do not focus on the same objective, they enable us to strengthen our focus on real-time processing and presentation instead of storing images over time.

Further research has been done in the augmentation of interaction and visualization. See et al. [16] explored the topic of haptic feedback to improve tactile experience when rendering 3D, and Tang et al. [17] explored the concept of touch-based interface in the Metaverse to support item interactivity. DICOM Supplement [18] defined mechanisms of wrapping up STL models in the DICOM files, thereby supporting our study of linking the traditional 2D medical images to the corresponding 3D images. Pereira et al. [19] explored web-based DICOM renderings and emphasized the visualization within browser settings and also have the facilitation of the live interactive 3D rendering directly based on the input DICOM data. The PyVista documentation [20] highlights the modern technologies of rotation of objects, stress visualization, and lighting control features added to our system to allow a more moving and user-friendly experience of the visualizing process.

III. METHODOLOGY

The suggested system in this research will seek to select a method that will facilitate the conversion of crude medical DICOM slices into high-end interactive 3D anatomical images. We used a four-stage methodology, namely, real data collection, preprocessing steps, 3D reconstruction, and interactive exploration. The methodology of this study is represented in Figure 1.

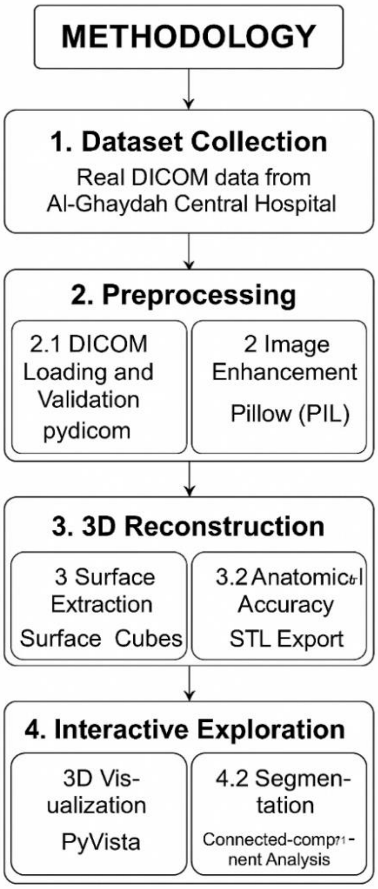


Fig. 1. An overall framework of proposed method.

A. *Compilation of Datasets*

In this study, actual medical imaging data of Al-Ghaydah Central Hospital, Al-Mahrah in Yemen, was utilized. This data set is made of real DICOM files that are in service by CT and MRI tomographies. All DICOM files were anonymized in order to ensure the privacy of medical data protection. The data set has 30 folders of 30 personalities as DICOM files. An example of folder statistics is contained in Table 1. This actual data is a credible approach to testing the validity of our strategy.

TABLE I. SHOWS DATASET CHARACTERISTICS

Datasets	# of slides	Folder size	Resolution
D1	120	60.2 MB	Low
D2	386	139 MB	Medium

D3	545	273 MB	High
D4	827	415 MB	Very High

B. *Data Preprocessing*

The preprocessing step took raw DICOM slices in order to improve the quality of medical images through the following steps:

· DICOM files loading and verification: Each DICOM file is loaded, and its pixels and metadata are taken out using the pydicom package. Unacceptable or unfinished files are deleted. Next, the automatic sorting of slices based on SliceLocation properties was performed in order to provide an anatomical sequence.

· Image enhancing: Pillow (PIL) is used to enhance discernment of anatomical features. This is an improvement of contrast noise, correction, and sharpening. This is an action that supports the visualization and also segmentation.

· Volumetric preparation The optimized slices are arranged in a 3D volumetric array with the NumPy library with preservation of accuracy and clarity based on the metadata. The step produces a high-resolution and appropriate volumetric model that can be used in surface extraction.

C. *3D Reconstruction*

The 3D reconstruction stage transforms the already prepared volumetric representation into a polygonal surface representation by the following steps: First, Surface Extraction: The Marching Cubes algorithm (scikit-image) is used to compute surface vertices and faces. In this implementation, the Marching Cubes method uses an automatically chosen isosurface value that is the average intensity of the volumetric data. This technique doesn't require manual threshold calibration and works well with datasets that have varied intensity distributions. By using voxel spacing parameters (pixel spacing and slice thickness) from DICOM metadata, the spatial precision of the reconstructed surface is kept. The output of this stage is a triangular surface mesh made up of vertices and faces. This is what we use to see and cut things up. of the volumetric density field. The method is quite useful in creating a smooth polygonal mesh representing the anatomical surface. Measurement of space is sustained with the aid of metadata obtained through DICOM in order to build up a model, which is capable of depicting realistic anatomical levels. This guarantees medical research and image representation applicability in the future. Lastly, Exporting Files: The generated model is converted to an STL file, which can be easily compatible with 3D printing technology and even visualized externally.

D. *Interactive Exploration*

Lastly, the reconstructions of the 3D model are shown in the interactive viewing environment with the PyVista module. Such a visualization structure allows dynamic interactive visualization by means of smooth rotation, zooming, lighting effects, and colorization of the depicted sections. These functions increase depth and structure by making it clear. Moreover, automated segmentation is supported by the analysis of connected components on the extracted grid in which detached pieces of the anatomy are determined and marked with specific color markings. Such a segmentation process enhances the interpretability of the model and allows distinguishing certain structures in the volumetric data.

The system has a user-friendly graphical interface, which is made with Tkinter such that there is a smooth interaction with the user. This enables the users to freely move among 2D slices, modify optimization settings, start reconstructions, and view the resultant 3D model without technical challenge. We used multithreading to ensure that the interface was responsive because the operations like surface extraction using Marching Cubes and the network segmentation are lengthy and demand several computations. Through the use of intensive processing in back-end threads, the system also does not experience congestion of the interfaces and delay of data processing and enables the user to experience a flow and continuous interface even during the processing of large DICOM files. This developmental approach to design improves the usability of the system, its efficiency, and its appropriateness to both clinical and research use.

E. **A.** *Performance Measurement Criteria*

For quantitative evaluation, performance tests were done on both the reconstruction and segmentation processes. We measured reconstruction time from the start of volumetric processing to the end of surface mesh production. The time it took to segment was measured from the start of connectivity-based mesh analysis to the end of region separation. All measurements were conducted in a CPU-based environment without GPU acceleration to simulate authentic deployment settings.

Algorithm 1: DICOM 3D Reconstruction System

```
Algorithm 1: DICOM 3D Reconstruction System
Input: Folder containing DICOM images
Output: 3D reconstructed model (with optional segmentation) and STL file

//Load DICOM Dataset
  BEGIN
    ASK user to select DICOM folder
    FOR each file in folder DO
      IF file is DICOM THEN
        READ file and add to SliceList
      END IF
    END FOR
    SORT SliceList by slice position
  END
//Preprocessing and Volume Construction
  BEGIN
    CREATE empty 3D Volume V
    FOR i ← 1 TO length(SliceList) DO
      INSERT SliceList[i].pixels into V
    END FOR
  END
//Slice Visualization and Enhancement
  BEGIN
    WHILE user browses slices DO
      DISPLAY current slice
      IF user adjusts enhancement THEN
        APPLY enhancement to slice
      END IF
    END WHILE
  END
//3D Reconstruction
  BEGIN
    APPLY Marching Cubes to Volume V
    GENERATE meshM (vertices and faces)
    DISPLAY in 3D viewer
  END
//Segmentation (Optional)
  BEGIN
    IDENTIFY connected components in mesh M
    ASSIGN  colors to components
    DISPLAY segmented model
  END
// Export 3D Model
  BEGIN
    ASK user to choose save path
    SAVE mesh M as STL file
  END
//Threading Support
  BEGIN
    RUN complex operations in background threads
    MAINTAIN GUI to response
  END
```

IV. EXPERIMENTAL RESULTS AND PERFORMANCE EVALUATION

A. *Experimental Setup*

We used real clinical DICOM datasets from CT and MRI scanners at Al-Ghaydah Central Hospital in Yemen to test the proposed system. The tests were done on a normal workstation with an Intel Core i5 processor, 12 GB of RAM, and no GPU acceleration. This made sure that the performance results were reasonable. All of the tests were done in Python. We used pydicom to handle DICOM files, NumPy to analyse volumes, scikit-image to build surfaces, and PyVista to show the results.

B. *Reconstruction Time Analysis*

Reconstruction time was measured from the initiation of volumetric processing to the completion of 3D mesh generation. Table 2 presents the average reconstruction time for different quality modes, and the results demonstrate that the system scales predictably with dataset size while maintaining interactive performance.

TABLE II. RECONSTRUCTION TIME ACROSS DIFFERENT DATASET SIZES AND QUALITY MODES

Quality Mode	D1 (s)	D2 (s)	D3 (s)	D4 (s)
Low	1.67	1.94	2.32	3.05
Medium	2.4	4.17	5.76	7.20
High	5.83	6.10	8.28	15.30

C. *Segmentation Time Analysis*

The time it took to segment (cut) was measured from the start of the connectivity-based mesh analysis to the end of the region separation and visualisation. Table 3 shows how long it takes to segment different sizes of datasets on average. The results show that the time it takes to segment increases in direct proportion to the complexity of the mesh, yet it stays within interactive boundaries that are good for real-time exploration.

TABLE III. AVERAGE SEGMENTATION TIME FOR DIFFERENT DATASET SIZES AND QUALITY MODES

Quality Mode	D1 (s)	D2 (s)	D3 (s)	D4 (s)
Low	23.48	24.95	56.15	74.9
Medium	101	163	439.30	459.8
High	53	75	191.80	243

D. *Mesh Complexity Evaluation*

The Marching Cubes approach was used to objectively measure the geometric complexity of the reconstructed models by counting the total number of vertices and triangular faces created for each dataset. These measurements show directly how well the surface resolution and anatomical detail were captured during reconstruction. Table 4 shows that the number of vertices and faces goes up in direct proportion to the quantity of the dataset and the volumetric resolution. This shows that the method can keep delicate anatomical structures even when the input gets more complicated. More vertices and faces provide smoother surfaces and a better depiction of complex anatomical boundaries, which are important for accurate medical visualisation, segmentation, and possible future uses like simulation and 3D printing. Even though the shapes were more complicated, the meshes that were made were still good for interactive visualisation. This showed a good balance between model fidelity and computational practicality.

TABLE IV. THE NUMBER OF VERTICES AND FACES IN RECONSTRUCTED 3D ANATOMICAL MODELS

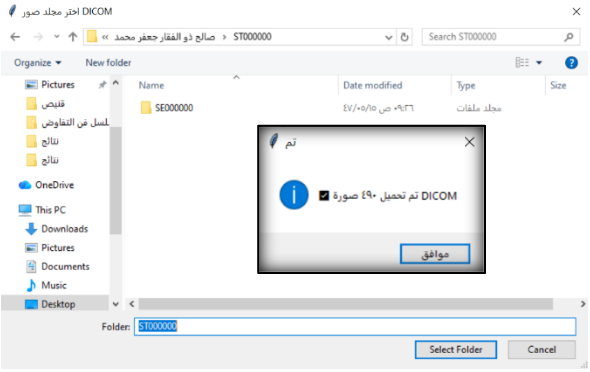
Dataset	Vertices	Faces
D1	838,528	1,669,674
D2	1,838,817	3,667,638
D3	3,008,392	6,006,136
D4	4,515,859	9,010,772

E. Effect of Quality-Based Optimization

The quality-based optimisation technique offers a feasible compromise between the speed of reconstruction and the level of detail on the surface. The low-quality mode speeds up processing time by volumetric downsampling, and the high-quality mode improves anatomical continuity by Gaussian smoothing. This makes the system flexible enough to work with different clinical and computational needs. The experimental results show that the suggested method can quickly turn raw DICOM data into interactive 3D models without losing any anatomical correctness. With the help of metadata-aware volumetric building, optimised Marching Cubes reconstruction, and multithreaded execution, it's possible to interact with even the largest clinical datasets in real time.

V. RESULTS AND DISCUSSION

The developed DICOM3DApp boasted of high efficiency and accuracy in transforming the 2D DICOM CT images to the interactive 3D anatomical models. Various datasets of different magnitudes were used to evaluate the system in terms of its resilience, responsiveness, and suitability to different reconstruction requirements. The outcomes of the evaluation confirm the program to be skilled in loading, preprocessing, visualizing, reconstructing, segmenting, and exporting data in a powerful and user-friendly atmosphere. Figure 2 illustrates the leading of DICOM files.



☑ تم تحميل ٤٩٠ صورة DICOM

Folder: ST000000

Fig. 2. DICOM Loading and Metadata Interpretation Process.

In Figure 2, it can be seen that during the data loading and preparation stage, all DICOM files were correctly identified with the help of the pydicom library and sorted with regard to their SliceLocation values to ensure anatomically coherent reconstruction. This approach was successful in retrieving impactful metadata, such as PixelSpacing and SliceThickness, thereby preserving their correct geometric ratios at the volumetric assembly. The slices represented through the interactive viewer that provided easy navigation and the enhancement tools on contrast and sharpness significantly improved the sharpness of the soft tissue and bone lines. Preprocessing phases are used to refine the quality of 3D models by offering clean and visually uniform contributions, as in Figure 3.

The volume data were transformed into a three-dimensional representation of the surface with the Marching Cubes algorithm in scikit-image. The process had a consistent result of anatomically accurate models at various levels of reconstruction quality (low, medium, and high). The lower-resolution models allowed quick previewing, but high-resolution reconstructions would express complicated anatomy, such as subtle bone edges and soft-tissue boundaries. The last stage involved developing the 3D models in PyVista (Figure 4), and the models could be rotated, zoomed, and interactively inspected. As an example, it is possible to see how the 3D model can be rotated either using touch or using the mouse pointer (Figure 5) or the percentage of the zoom (Figure 6). Moreover, the mesh connectivity-based segmentation was used to provide a more accurate description of the anatomical structures, assigning specific colors to each one, increasing interpretability, and facilitating the educational and analytical objectives. as shown in figure 7. The resulting meshes could be exported in the form of STL format, which allowed them to be supported by 3D printing processes as well as external visualization software.

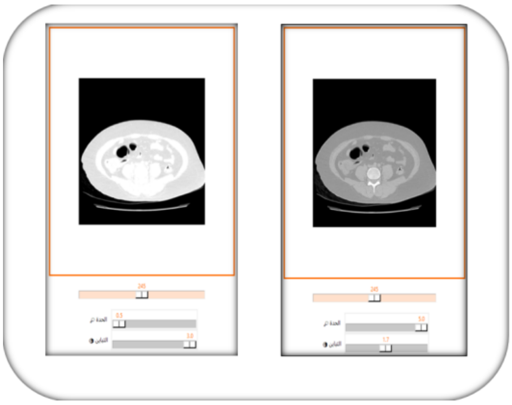


Fig. 3. Preprocessing Phase Demonstrating Noise Mitigation and Intensity Standardization

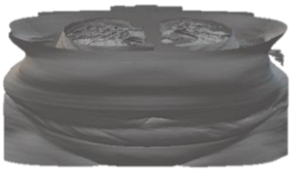


Fig. 4. Comprehensive 3D reconstructed model derived from all DICOM slices (in gray).

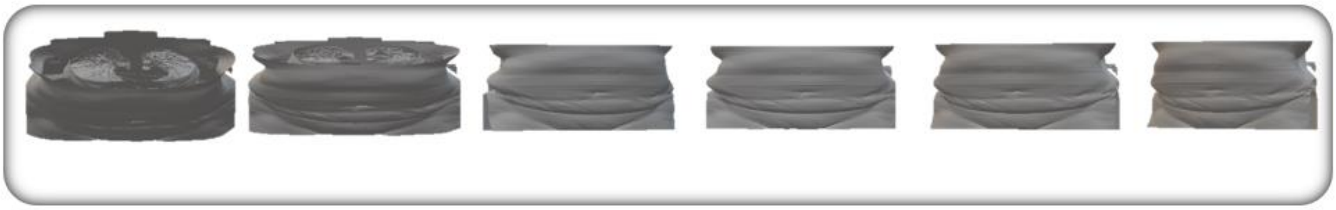


Fig. 5. An interactive 3-D model controlled by touch and mouse pointer.

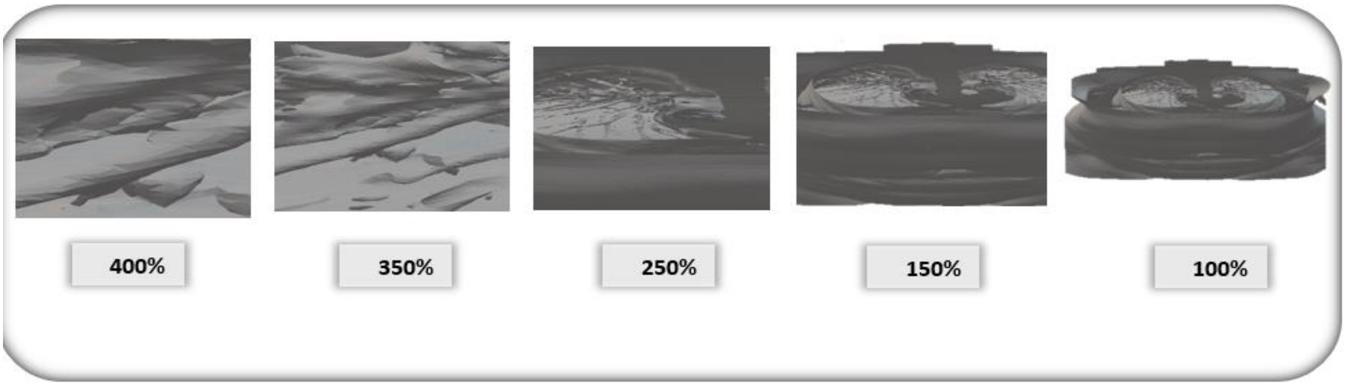


Fig. 6. A zoomed-in view of the model with high resolution.

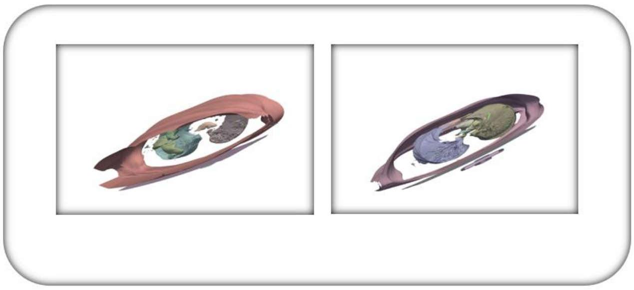


Fig. 7. Segmented 3D model with color-coded components, illustrating separate anatomical structures.

Table 5 shows that the system responsiveness always was high because of the employment of the multithreading features of Python. Reconstruction and segmentation, which require resources to perform, were done in the background enabling the graphical user interface to be fully interactive. Data sets with 100 and 800 slices were processed without failures and delays. The time to reconstruction was related to the size of the data set and hence a small data set required 1-3 seconds and a large data set (up to 800 slices) required 3-5 seconds depending on the quality level selected. The range of segmentation time has been between 1 and 8 minutes and increased with model complexity. Notably, the GUI was made smooth throughout the entire studies, with each stage, which included loading, processing, displaying, and exporting, functioning properly. Scalability, reliability, and real-time interaction make the system suitable both in the academic research and the educational as well as therapeutic use.

TABLE V. . DEMONSTRATES THE CORRELATION AMONG PROCESSING TIME, DATASET DIMENSION, AND QUALITY.

Dataset	**Quality**	**Reconstruction Time (sec)**	**Observed Detail**	**GUI Responsiveness**	**3D model splitting time(sec)**
100 slices	Low	1	Moderate	Smooth	23
200 slices	Medium	4	High	Smooth	158
250 slices	High	6	High	Smooth	80
400 slices	High	8	High	Smooth	191
800 slices	High	15	High	Smooth	243

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VI. CONCLUSION AND PROSPECTIVE RESEARCH

This paper presents an all-purpose and flexible method of transforming the DICOM-based computed tomography (CT) data into interactive three-dimensional formats. The DICOM3DApp is useful in links the conventional 2D slice understanding with the experience of the 3D anatomy through the combination of pydicom as metadata manager, NumPy as volumetric generator, and PyVista as real-time display. It has a user-friendly interface that enables navigation through slices, enhancement filters, rebuilding surfaces and performing segmentation thereby enabling the user to view anatomy with much more clarity and precision. The results suggest that the system is effective producing high fidelity 3D meshes without compromising GUI responsiveness even during handling of large data sets, which is why it is suitable in medical research, educational contexts and initial clinical visualization. Moreover, the combination of the segmentation and connection analysis allows a better understanding of anatomical regions with facilitation of color code structural difference. The ability to export reconstructed models in STL format increases the applicability of the system in 3D printing, surgical planning and training based on simulation. Combined with the computational efficiency, modular structure, and user-friendly interface, the proposed system can be considered a reliable and accessible tool in modern medical imaging procedures.

It will focus on improving the abilities of the system in the future to address the changing needs in medical visualization. One of the solutions is the inclusion of deep-learning segmentation algorithms to enhance anatomical borders identify, and reduce the amount of manual preprocessing. Additionally, improved rendering pipelines would have a more fluid real-time display, particularly to be compatible with virtual reality (VR) and augmented reality (AR) systems. Developing a web-based version of the system would support remote work as physicians and researchers will be able to interpret 3D models in different places. Further enhancements can include the use of gesturing through the computer vision algorithm, allowing the user to edit the 3D model through hand motions captured using a camera, hence creating an even more engaging and naturally involving exploring experience. All these changes would improve the system to become a next-generation medical visualization platform that is skilled in advanced diagnostic, educational, and clinical procedures.

AUTHORS' CONTRIBUTIONS

Conceptualization, A.K.A., A.B.A., and M.R.A..; Methodology, N.H.A., A.S.B., and K.H.B..; Validation, N.A.M.; Writing Original Draft Preparation, A.K.A., A.B.A., Writing Review & Editing, K.H.B., and N.A.M.; Supervision, K.H.B. and A.S.B.

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