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3D Geometric Segmentation Method based on the Point-normal Form Equation of a Plane

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Abstract

Under the background of rapid development of computer technology, mature 3D modeling technology and extensive application of 3 D model, the research of 3 D geometry cutting is of great significance. In this paper, the surface cutting method is adopted to determine the cutting plane based on the point method of the surface, the 3D geometric figure center is selected as the point, and the cutting plane equation is obtained by calculating the normal vector at a given Angle. Using the VTK function library, 3D geometry reading, cutting, after cutting graph data retention and translation separation are realized in Python, and then the cutting plane is displayed. Taking the planning of impacted third molar cutting path in dental medical images as an example, we verify the practicability and flexibility of the algorithm, which has application potential in many fields such as medical treatment and relic restoration.

Keywords

3D Model; VTK; Geometric Center; Normal Vector; Plane Cutting.

1. Introduction

Computer technology has entered a new era of exponential development. Driven by the coordinated efforts of the fifth-generation mobile communication (5G) network, cloud computing infrastructure, and edge computing technology, the global digitalization process has shown explosive growth. Especially in the field of computer graphics, with the breakthrough progress of ray tracing technology, the continuous optimization of physical engine algorithms, and the geometric improvement of the parallel computing capabilities of GPUs, 3D modeling technology has achieved a leapfrog development from laboratory research to industrial application. According to the latest report from the International Data Corporation (IDC), the global data volume of 3D models is surging at a compound annual growth rate of 67.3%, and it is expected to exceed the scale of 2.8 ZB by 2025. This explosive growth of data mainly stems from the strong demand of emerging technologies such as Industry 4.0, the metaverse, and digital twins.

In terms of application dimensions, 3D modeling technology has deeply penetrated into interdisciplinary fields: In the medical field, through the 3D reconstruction technology of CT/MRI images, accurate visual positioning of organ lesions has been achieved; In the field of cultural relics protection, sub-millimeter 3D scanning technology has been used to complete the digital archiving of 57 caves in the Mogao Grottoes in Dunhuang; In the field of industrial design, with the help of the parametric modeling system, the product research and development cycle has been shortened by more than 40%; In the cultural and creative industry, the Nanite virtual geometry technology of Unreal Engine 5 has made real-time rendering of film and television-level image quality possible. It is worth

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noting that with the breakthrough of deep learning algorithms such as Neural Radiance Field (NeRF), 3D modeling is evolving from traditional manual modeling to intelligent generation.

Against this background, the basic research on the geometric cutting technology of 3D models has great scientific value and engineering significance: In the field of precision medicine, the virtual cutting system based on haptic force feedback can assist surgeons in rehearsing tumor resection surgery. Clinical trials have shown that this technology can reduce the intraoperative blood loss by 28%; In the field of archaeological restoration, the computed tomography cutting algorithm has been successfully applied to the virtual piecing and restoration of the bronze wares from Sanxingdui, and the restoration efficiency has been increased by more than five times; In the field of advanced manufacturing, the intelligent cutting optimization system based on finite element analysis can reduce the weight of the blades of aero engines by 15% while maintaining the structural integrity. These breakthroughs mark that the 3D model processing technology has developed from a simple geometric operation to an interdisciplinary research system that integrates material properties, physical attributes, and intelligent algorithms [1].

In recent years, numerous researchers have explored this field. Ning Jiao, Dong Xiao, and Feng Zongxue[2] proposed an algorithm for arbitrary-angle planar cutting based on the point-normal form equation in Cartesian coordinates. While effective, the method's directional intuitiveness was limited, prompting the integration of polar coordinates to enhance clarity. Their VTK-based implementation achieved efficient multi-plane cutting, demonstrating feasibility and flexibility. Dong Kai, He Jie, and Wang Yue[3] developed a vector-based algorithm for single-object segmentation of UAV oblique photogrammetry 3D models. Simulations showed superior sensitivity, specificity, and accuracy compared to traditional methods, highlighting its engineering value. Shi Keyi[4] introduced a controllable-range STL model segmentation method that precisely removes targeted regions, extendable to arbitrary planar cutting. Tao Youlong[5] devised a feature-point-based algorithm to compute optimal paths and topological structures for model segmentation. Lei Jiangtao, Liu Qing, Pan Chanling, et al[6] proposed a physical cutting method using vector boundaries for large-scale oblique 3D models, validating its logical robustness, computational efficiency, and reliability in extensive experiments.

The cutting of 3D geometric figures is widely applied in real life. The point-normal form method adopted in this paper can quickly calculate the equation of the cutting plane. Secondly, we use the functions in the VTK library for 3D visualization and planar cutting of 3D geometric figures. During the cutting process, the cut-off parts are retained, enabling researchers to clearly observe how the 3D geometric figures are cut and the effect after cutting. This greatly enhances the practicality of the algorithm and fully demonstrates the engineering practical value and multi-dimensional expansion potential of intelligent algorithms in 3D space analysis.

2. Principle of Cutting Algorithm

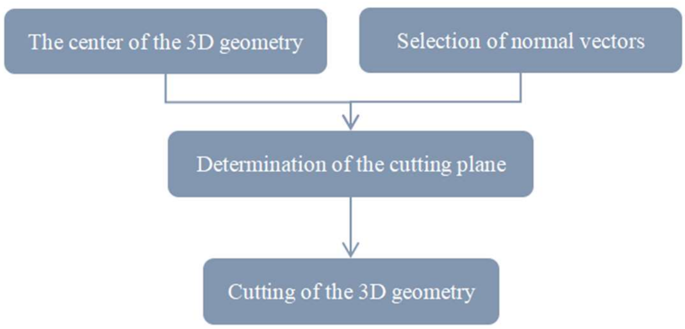

Fig. 1. Cutting flow chart

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Given a predefined cutting angle, this paper employs planar cutting to perform segmentation operations on 3D geometric models. The core of the study lies in determining the cutting plane, which can be defined using the point-normal form equation of a plane. This equation requires specifying a point on the plane and its normal vector. The operational procedure involves: determining the centroid of the 3D geometry, selecting the normal vector based on the cutting angle, establishing the cutting plane equation via the point-normal form, and performing the cutting operation on the 3D geometry, As shown in Fig. 1.

First, the center of the 3D geometric shape is selected as the required point. The selection of this point can be random but must consider practical scenarios. This study investigates both regular and irregular 3D geometric shapes as examples. For regular 3D geometries, their centers can be easily determined through geometric analysis. In contrast, for irregular 3D geometries, functions from the VTK library can be employed to identify their centers. In this research, we primarily focus on regular 3D geometric shapes, using their geometric centers as the central points for cutting operations. Furthermore, these geometric centers are designated as the origin of a Cartesian coordinate system, establishing a spatial reference framework for subsequent analysis.

Secondly, set the angle of the cutting plane as required. Assuming the cutting angle for the 3D geometric shape is θ. Calculate the normal vector of the cutting plane under this premise.

Suppose the normal vector of the plane is $\vec{n} = (A, B, C)$ .The normal vector of the xOy plane passing through the origin is $\vec{k} = (0,0,1)$,through the dot product formula of vectors:

$$\vec{a} \cdot \vec{b} = |\vec{a}||\vec{b}| \cos\varphi \quad (1)$$

Among φ is the include angle between $\vec{a}$ and $\vec{b}$.

The result calculated through the dot product formula is $C = \pm \cot \varphi \sqrt{A^2 + B^2}$.

Therefore, it is concluded that the equation of this cutting plane is

$$Ax + By \pm \cot\theta \sqrt{A^2 + B^2} z = 0 \quad (2)$$

Therefore, it is concluded that the equation of this cutting plane is

$$Ax + By \pm \cot\theta \sqrt{A^2 + B^2} z = 0 \quad (3)$$

However, since there are infinitely many normal vectors for a plane. We might as well consider a special case(Here we assume that $A^2 + B^2 = 1$). Find out $C = \pm \cot\varphi$,the normal vector $\vec{n} = (A, B, \pm \cot\theta)$ of the cutting plane can be obtained by this method. Therefore, the equation of the cutting plane at this time is

$$Ax + By \pm \cot\theta z = 0 \quad (4)$$

However, there is another situation here. When the origin of the rectangular coordinate system is not the midpoint of the 3D geometric figure, we take the center as (x_0, y_0, z_0) .

The equation of the tangent plane at this time then becomes

$$A(x-x_0)+B(y-y_0)\pm\cot\theta\sqrt{A^2+B^2}(z-z_0)=0 \quad (5)$$

Finally, after the cutting plane is determined, the next step is to perform the cutting operation on the 3D geometric figure. The 3D geometric figure is cut into two parts by this plane. Compared with the traditional cutting method, we retain the cut-off parts and separate them at the same time, as shown in Fig. 2.

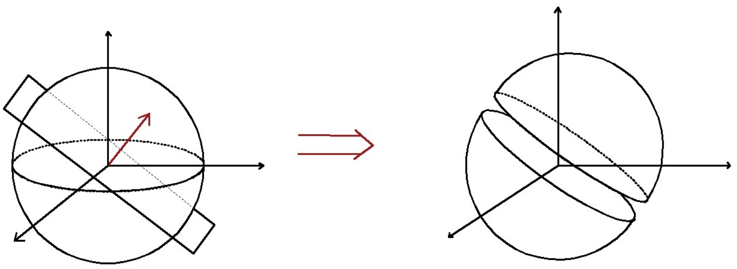

Fig. 2. Display diagram of the cutting

In this figure, on the left side of the figure, we establish a rectangular coordinate system with the center of the sphere as the origin of coordinates. Through the origin and the included angle, we determine the normal vector of the cutting plane (the red part in the figure), and then obtain the equation and image of this cutting plane. On the right side of the figure is the image of us cutting this sphere into two parts through this cutting plane. The outer normal vectors and inner normal vectors of the two cutting surfaces are collinear with the normal vector of the cutting plane.

3. The Implementation of the Algorithm

3.1 Implementation of Regular 3D Geometric Figure Cutting

The implementation of the algorithm is based on the function library in VTK. VTK (Visualization Toolkit) is an open - source, cross - platform 3D visualization and graphics processing library. Since its release in 1993, it has become a benchmark tool in the field of scientific computing visualization. Its core functions cover complex algorithms such as data modeling, 3D reconstruction, volume rendering, streamline simulation, and surface fitting, and it supports efficient rendering from point cloud processing to large - scale parallel data sets.

In the medical field, VTK is widely used for the 3D reconstruction of CT/MRI images and lesion segmentation, assisting doctors in making accurate diagnoses. In the engineering field, it can simulate the distribution of physical fields such as fluid mechanics and structural stress, and seamlessly interface with finite element analysis tools (such as ANSYS) to provide intuitive visual feedback.

VTK adopts a data flow pipeline architecture, modularizing steps such as data input (supporting DICOM, STL, CSV, VTK format, etc.), filtering processing (such as denoising, interpolation, clustering), and mapping rendering. Developers can quickly build applications through the high-performance C++ interface or concise bindings (such as vtkmodules) in languages like Python and Java. At the same time, it is compatible with OpenGL, WebGL, and modern GPU acceleration technologies, enabling real-time interactive visualization across platforms (Windows/Linux/macOS) and on the Web. Its open-source BSD license allows for the free integration of commercial applications. Together with upper-level tools such as ParaView, Mayavi, and 3D Slicer, it forms a complete ecosystem from scientific research to industry. With an active community, detailed documentation, and continuous updates supporting artificial intelligence-driven data processing (such as integration with PyTorch/TensorFlow), it is the preferred solution for both the academic and industrial sectors to address the challenges posed by multi-dimensional, dynamic, and heterogeneous data.

In the implementation of Python code, we will call the corresponding reader functions in VTK according to different file formats. For example, for.stl files, we will use the vtkSTLReader() function; for.vtk files, we will use the vtkPolyDataReader() function; and for.obj files, we will use the vtkOBJReader() function. Through these readers, we can load the 3D geometric graphic data from files in different formats into the memory, preparing for the subsequent cutting operations. As shown in Fig. 3 below.

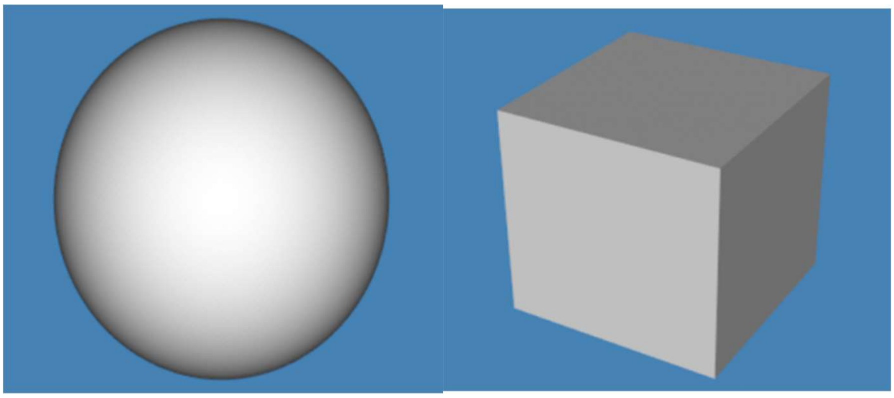

Fig. 3. Display of Regular 3D Geometric Figures

In the program, we need to use the midpoint of the 3D geometric figure and the normal vector of the cutting plane. We use polyData.GetCenter() to calculate the center of the geometric figure data. We use SetCenter(Center) and SetRadius() to mark the geometric center of the 3D geometry with a red sphere.

```
>>center = polyData.GetCenter()
>>centerSphere = vtk.vtkSphereSource()
>>centerSphere.SetCenter(center)
>>centerSphere.SetRadius(0.1)
>>centerSphere.Update()
```

On the premise of obtaining the center point, for the cutting plane, we need to set it to the center of the data using SetOrigin(Center) and take this point as the origin of the rectangular coordinate system. Then, use SetNormal(x, y, z) to set the normal vector of the cutting plane. By calling the two functions SetOrigin() and SetNormal(), the corresponding cutting plane can be obtained.

```
>>plane = vtk.vtkPlane()
>>plane.SetOrigin(center)
>>plane.SetNormal(x, y, z)
```

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3.2 Display of the Cutting Results of Regular 3D Geometric Figures

In the program, we ingeniously use the GetOutput() function to retain the geometric figure data after cutting (the upper part in the figure), and use the InsideOutOn() function to retain the geometric figure data of the other part.

The use of these two functions enables us to clearly see how the 3D geometric figure is cut and the effect after cutting. Compared with traditional cutting methods, the method adopted in this paper is more practical and versatile.As shown in Figure 4 below.

```
>>upperPolyData = clipperUpper.GetOutput()


>>clipperLower.InsideOutOn()
>>clipperLower.Update()
```

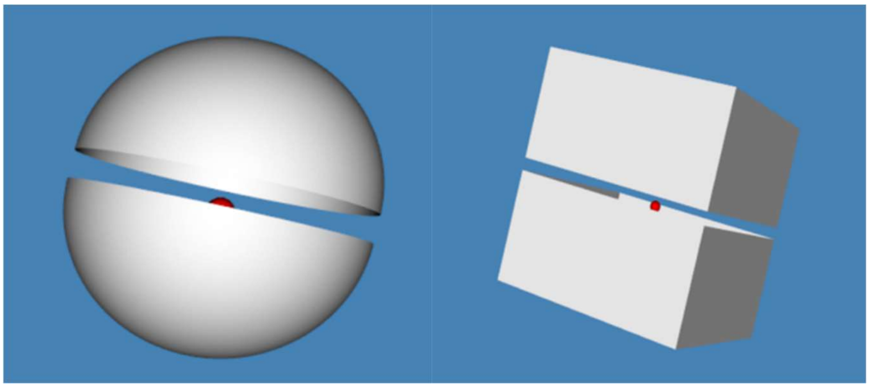

Fig. 4. Display of the Cutting of Regular 3D Geometric Figures

Secondly, the distance of the translation transformation is set by adjusting the transform.Translate(i, j, k) function. It is set to move in the negative direction of the normal vector to separate the cut geometric figures. In this way, one cutting and separation operation on the 3D geometric figure is completed.

```
>>transform = vtk.vtkTransform()
>>transform.Translate(i, j, k)
```

When displaying the cutting plane, we first obtain the data of the model's bounding box to ensure that the size of the generated cutting plane matches appropriately. The GetBounds() function can be used to obtain the boundary data of the three coordinate axes in the rectangular coordinate system.

Finally, we create the cutting plane through the vtkPlaneSource() function in the VTK function library to visualize the cutting plane, as shown in Figure 5 below.

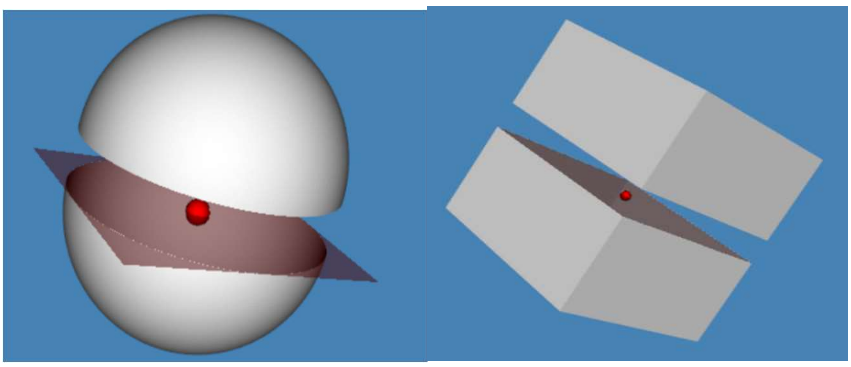

Fig. 5. Display of the Cutting Plane of Regular 3D Geometric Figures

3.3 Cutting and Display of Irregular 3D Geometric Shapes

This method can not only be used to study regular 3D geometric figures but also be extended to irregular 3D geometric figures. The principle of cutting 3D geometric figures is the same. The point-normal form method is adopted to calculate the equation of the cutting plane. Since it is difficult to directly obtain and mark the geometric center of an irregular 3D geometric figure, here we can also accurately find the center of the irregular 3D geometric figure by using the functions of the VTK library that are used to find the center of a regular 3D geometric figure. Eventually, the irregular 3D geometric figure can be cut according to different requirements, as shown in Fig. 6 below.

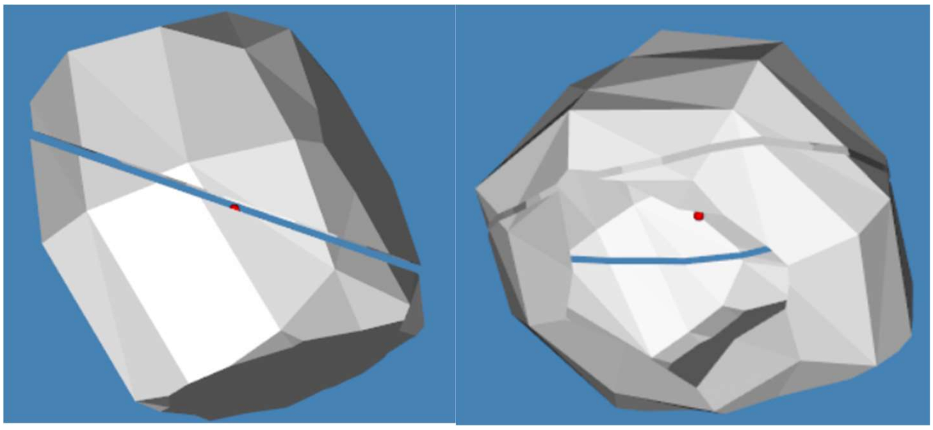

Fig. 6. Cutting of Irregular 3D Geometric Figures

4. The Application of the Algorithm

4.1 Experimental Environment

It is implemented in Visual Studio software with the VTK library configured under the Windows system.

4.2 Experimental Content

First, we adopted CBCT (Cone Beam Computed Tomography) image data as the basic dataset for our research. As an advanced medical imaging technology, CBCT is capable of generating high-resolution three-dimensional images and is widely applied in multiple medical fields such as oral and maxillofacial surgery, otolaryngology, and radiotherapy. The CBCT image data we used is stored in Dicom format.

Dicom, which stands for Digital Imaging and Communications in Medicine, is an internationally recognized standard file format and communication protocol in the field of medical imaging. It provides a unified specification and standard for the storage, transmission, and sharing of image data and related information generated by medical devices (such as CT, MRI, ultrasound, etc.). By adhering to the Dicom standard, seamless interoperability can be achieved among medical devices manufactured by different vendors, ensuring that medical imaging data can flow efficiently and accurately within hospitals and between different medical institutions. This, in turn, provides a solid data foundation for clinical diagnosis, treatment planning, and medical research.

Secondly, we use the vtkDICOMImageReader() function in the VTK function library to read this Dicom file. For the output of the VTK function images, we use the vtkImageViewer2() function in VTK to render the 2D data for the frontal, top, and side views and to render the 3D data for the 3D reconstruction view. As shown in Fig. 7 below, the three images on the left are the 2D data rendering images, and the image on the right is the 3D data rendering image.

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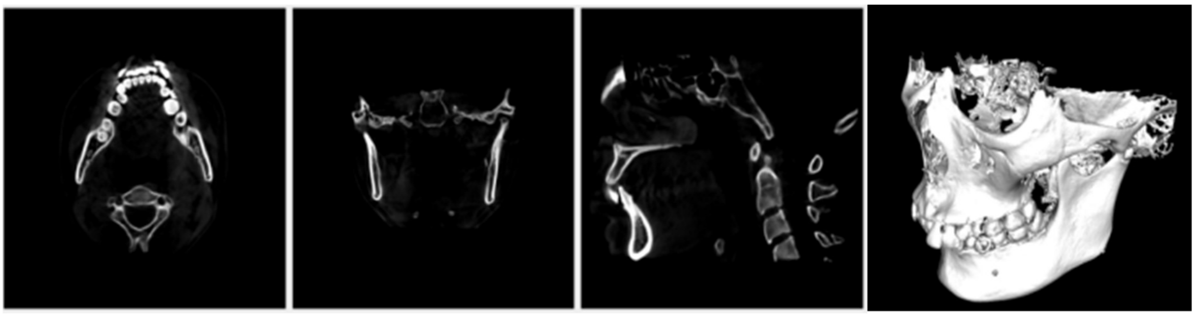

Fig. 7. CBCT Image and 3D Reconstruction Output Diagram

This study focuses on constructing a digital pathway planning system for precise osteotomy and tooth division in horizontally impacted mandibular third molars.

The horizontally impacted mandibular third molar is located at the terminal end of the mandibular dental arch, adjacent to the distal side of the second molar and proximate to the anterior border of the mandibular ramus. Due to insufficient mandibular development in modern humans, which often fails to provide adequate eruption space, this tooth typically remains horizontally impacted. Its crown long axis is nearly parallel to that of the second molar, with the crown apex frequently abutting the distal cervical region or roots of the second molar, creating mechanical obstruction and preventing normal eruption into the occlusal plane.

Anatomically, the crown of horizontally impacted wisdom teeth is often covered by mandibular bone or gingival tissue. Furthermore, the root anatomy of horizontally impacted molars is complex, with approximately 60% exhibiting bifurcated or fused roots. Root apices may closely approximate or encase the inferior alveolar nerve canal, sometimes even traversing the canal wall, significantly increasing surgical complexity.

From an adjacency perspective, the lingual side of the wisdom tooth is adjacent to the lingual nerve, while the buccal side is near the buccal nerve, necessitating cautious flap reflection during surgery to avoid traction-induced injury. In some cases, root apices extend to the inferior mandibular border or approach the mandibular angle region, potentially requiring auxiliary osteotomy. Preoperative evaluation via panoramic radiography and cone beam computed tomography (CBCT) is therefore critical to precisely assess root morphology, bone resistance, and three-dimensional spatial relationships with neurovascular structures. This enables the planning of safe surgical pathways, thereby minimizing intraoperative complications, as illustrated in Fig. 8 below.

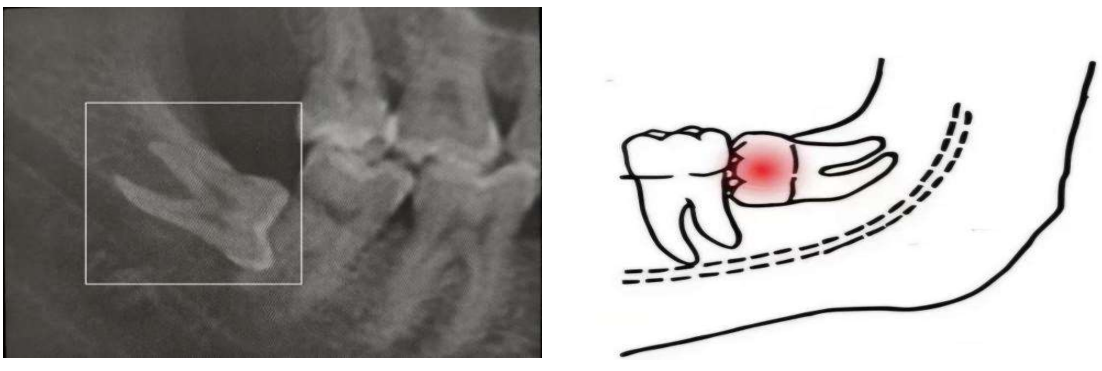

Fig. 8. Horizontally Impacted Mandibular Third Molar

In the domain of conventional oral surgery, the extraction of impacted third molars remains a clinically challenging procedure with multiple unresolved technical limitations. The most prominent issue is restricted visual field accessibility-due to the confined intraoral space and anatomically complex architecture, surgeons often face significant line-of-sight obstructions, hindering comprehensive visualization of the impacted third molar and its surrounding tissues. Furthermore, extensive operational blind zones exacerbate these challenges. When relying solely on unaided visualization and conventional instruments, surgeons cannot accurately localize or assess the spatial morphology of certain regions of the impacted tooth, which substantially amplifies procedural complexity and complication risks.

During the process of extracting impacted third molars, in order to remove the teeth from the alveolar bone more smoothly, the operation of cutting and separating the teeth is usually essential. However, in traditional methods, due to the lack of visual field and perception, the cutting operation often has a certain degree of blindness. Through the three-dimensional reconstruction of the oral cavity and the two-dimensional images of the teeth, doctors can clearly understand the growth situation of the impacted third molars, and then make a pre-operative plan for the cutting of the impacted third molars and formulate the cutting path. Finally, the impacted third molars are pre-segmented, the optimal cutting path is found according to different needs, and the teeth are removed in pieces to complete the tooth extraction operation, as shown in Fig. 9 below.

Among them, the normal vector used in ① is $\overrightarrow{n_1} = (0,1,0)$, the direction used in ② is $\overrightarrow{n_2} = (0,1,1)$, and the normal vector used in ③ is $\overrightarrow{n_3} = (0,0,1)$.

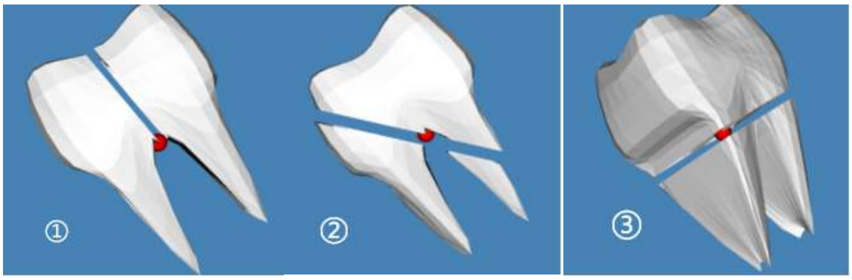

Fig. 9. Tooth Segmentation

5. Conclusion

In the field of 3D spatial analytics and geometric processing, achieving efficient and precise segmentation of 3D geometries has long been a critical research focus. This study advances methodologies for 3D geometric segmentation through rigorous theoretical analysis and experimental validation. We have successfully implemented planar cutting operations on 3D reconstructed geometries derived from complex medical imaging or other data sources, providing foundational technical support for downstream applications such as visualization analysis and simulation.

For cutting plane determination, we adopted the classical point-normal form mathematical framework. To establish a Cartesian coordinate system, the centroid coordinates of the 3D geometry were precisely computed using the GetCenter() function from the Visualization Toolkit (VTK) library. Designating this centroid as the origin of the coordinate system significantly streamlines subsequent mathematical operations and analytical workflows, thereby establishing a robust foundation for cutting plane definition. Notably, the selection of the origin can be adaptively optimized based on specific research objectives and geometric characteristics. For instance, when processing geometries with distinct symmetry axes or predefined reference points, assigning the origin to critical nodes along symmetry axes or designated reference points may enhance analytical precision and segmentation efficacy.

When a specific cutting angle for 3D geometric segmentation is predefined, we initiate a series of rigorous mathematical computations. Leveraging vector operations, trigonometric principles, and spatial coordinate data of the geometry, the normal vector of the cutting plane is analytically derived. This normal vector not only governs the orientation of the cutting plane but also critically determines the precision of subsequent segmentation procedures. Following the determination of the normal

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vector, the explicit equation of the cutting plane is formulated via the point-normal form equation, incorporating the precomputed origin coordinates. This step theoretically defines the spatial position and trajectory of the cutting operation.

Compared to conventional 3D geometric segmentation approaches, this study demonstrates significant advancements in data processing and visualization. We innovatively utilize the GetOutput() and InsideOutOn() functions from the Visualization Toolkit (VTK) library. The GetOutput() function enables precise extraction of target datasets from complex geometric structures, ensuring data integrity during segmentation. Meanwhile, the InsideOutOn() function provides unique visualization control, dynamically rendering the interaction between the cutting plane and the 3D geometry. This allows real-time observation of the progressive segmentation process and post-cut spatial relationships between segmented components. Through synergistic application of these functions, we achieve comprehensive, dynamic visualization of both segmentation workflows and outcomes, substantially enhancing operational intuitiveness and analytical fidelity.

6. Advantages

It is particularly worth noting that the cutting method proposed in this study has wide applicability and strong expandability. Whether it is a 3D geometric figure with regular shape and simple structure or an irregular 3D geometric figure with complex morphology and variable features, this method can effectively deal with it. In the field of practical applications, its potential should not be underestimated.

In the medical field, it can not only be precisely applied to the virtual cutting of teeth in stomatology, assisting doctors in preoperative planning and surgical simulation, and improving the safety and success rate of surgeries. It can also be extended to other disease-related research, such as the three-dimensional modeling and cutting analysis of tumor tissues, helping doctors to more clearly understand the growth morphology of tumors and their relationships with surrounding tissues, and providing a powerful basis for formulating personalized treatment plans.

In the field of cultural heritage protection, this algorithm can be used for the digital restoration and research of cultural relics. Through the three-dimensional reconstruction of damaged cultural relics, the cutting method is used to analyze the structural features of cultural relics, and then a scientific and reasonable restoration plan is formulated. At the same time, in terms of digital display, through the cutting operation, the internal structure and details of cultural relics can be displayed from different angles, enhancing the interest and attraction of cultural relic display.

This fully demonstrates the great engineering practical value of intelligent algorithms in three-dimensional space analysis, as well as their multi-dimensional expansion potential in interdisciplinary fields.

7. Disadvantages

However, no research achievement is perfect. The algorithm proposed in this study currently has certain limitations, mainly manifested in the need for users to manually adjust relevant parameters. In the actual operation process, this requires users to have a certain amount of professional knowledge and operational experience, and the operation process is rather cumbersome, failing to fully achieve complete intelligence.

In order to further enhance the performance of the algorithm and the user experience, subsequent research plans to deeply integrate cutting-edge technologies such as machine learning and deep learning. By constructing a large-scale dataset, the algorithm can automatically learn and optimize parameters from a large amount of data, realizing the automation and intelligence of the cutting process. For example, using the neural network model in deep learning to perform feature extraction and analysis on different types of 3D geometric figures, and automatically determine the optimal cutting parameters and strategies. Through such improvements, it is expected to significantly improve

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the intelligence level of the algorithm, lower the operation threshold for users, and provide more convenient and efficient technical support for applications in more fields.

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