

A 3D image processing system with shape editing capabilities: Volume Extractor Ver. 3.0

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1. Introduction

Volume Extractor (VE) is a practical 3D image processing software which was researched and developed at Iwate Prefectural University, Japan. The development of VE was initiated in 1998, and Ver. 3.0 is presently available for use. VE Ver. 1.0 and 2.0 specialized in the processing and visualization of 3D images^[1]. A 3D printer was installed at the university in 2005, and the demand for rapid prototyping (RP) triggered the development of specialized software (SMESH Ver. 1.0), which is capable of editing iso-surface shape data generated from medical images (e.g., bones, internal organs, and muscles)^[2]. Generally, isographic data generated from medical images contains imperfections (infinitesimal holes, surface inversions, etc.) due to the presence of unnecessary shapes and noise, and it necessary to remove these imperfections in order to generate output using a 3D printer or a rapid prototyping device. The primary function of SMESH Ver. 1.0 is reading the iso-surface data generated from a 3D image, then editing it by removing gaps, correcting the direction of surfaces, deleting garbage, and so on and eventually creating an STL file which can be used with 3D printers and rapid prototyping devices. Many actual models have been prepared using this software. Figure 1 shows an example of a bone model created by extracting the part corresponding to the knee joint and bones from a CT image of a knee. Figure 2 presents examples of models of part of the main brain and epidermis created from magnetic resonance (MR) images (T2 weighted images), and Fig. 3 shows an example model of the front part of a vase created on the basis of a CT image of a vase. The 3D printer used for the creation of these examples was Dimension 3D^[3].



Fig. 1. A sample of a bone model created with a 3D printer



Fig. 2 A sample of the brain created with a 3D printer)



Fig. 3 A sample of a vase created with a 3D printer

Since VE Ver. 2.0 and SMESH Ver.1.0 were separate pieces of software at that time, there were several aspects regarding the handling of data and the shape editing which were in need of improvement. For example, 3D images, such as medical images, contain unnatural pixel values referred to as noise (bruit) or artifacts. Furthermore, since there is a strong connection between segmentation and the reconstruction of the shape file, it is more effective to remove the noise and any unnecessary areas at the stage of 3D image processing, before performing the shape editing.

In order to resolve these issues, the functions of SMESH Ver. 1.0 were incorporated into VE Ver. 3.0 together with those of VE Ver. 2.0, and many new 3D image processing functions were added (e.g., 3D measurement, multivolume display capabilities, and histogram base segmentation). As a result, VE Ver. 3.0 can be used for transforming arbitrarily segmented 3D images into triangular polygon data, editing the resulting image, and creating actual models using a 3D printer or a rapid prototyping device. Figure 4 presents the main features and the structure of VE. In VE Ver. 3.0, it is possible to perform continuous processing of the inputted 3D image, including image processing, segmentation, image display, and 3D shape reconstruction. Furthermore, since the design of VE allows for all functions to be easily navigated through dialog menus, it is sufficiently usable even for individuals without experience in the field of 3D image processing.

In the present paper, focusing on VE Ver. 3.0, we explain the functions and the operation procedures for shape reconstruction by providing detailed examples^[4-6].

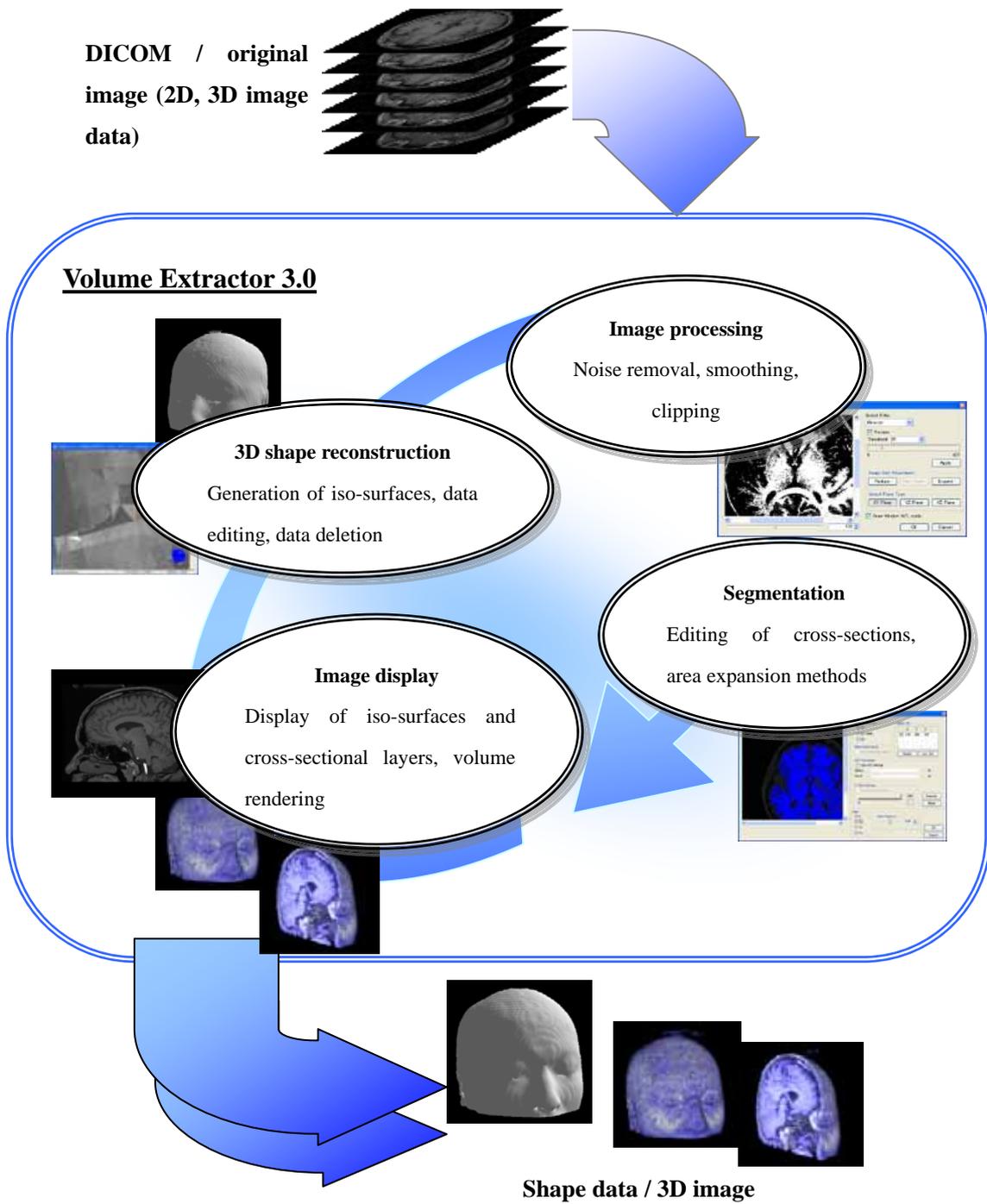


Fig. 4 Main functions and structure of VolumeExtractor 3.0

2. Overview of the functions

VE focuses primarily on the processing of medical imaging data, and offers the following set of functions^[4, 6].

- **Inputting DICOM images, such as medical images, and constructing 3D images**
- **Displaying multiple 3D images**
- **Extracting portions of 3D images (segmentation)**
- **Measuring 3D images**
- **Reconstructing and manipulating 3D images**
- **Outputting 3D image data and 3D shape data**

2.1 Inputting medical images and constructing 3D images

The software is compatible with reading MR and computed tomography (CT) medical images in the general DICOM image format. Furthermore, it is also compatible with image data in TIFF, BMP and RAW formats^{a)}. Figure 5 shows an example of constructing a 3D image from multiple 2D images and the approximation of its surface using 3D polygons.

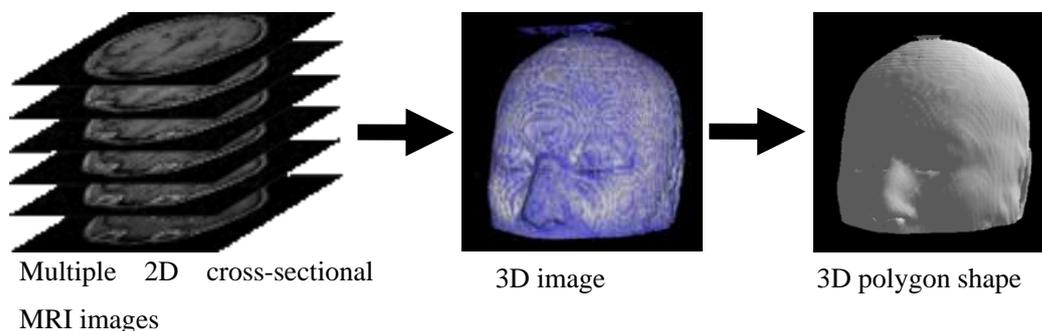


Fig. 5 Construction of 3D images and shapes

a) DICOM, RAW, TIFF

DICOM is an abbreviation of Digital Imaging and COmmunications in Medicine, and represents a standard for digital imaging and communication in medicine. By adopting the DICOM standard, it is possible to achieve uniformity of interconnections and databases of medical images between different devices. RAW indicates that the raw data has not been processed, and usually represents image data as pixel values when used as an image format. TIFF (Tagged Image File Format) is a widely adopted general-purpose image data format.

2.2 Displaying multiple 3D images

In VE, it is possible to display multiple 3D images at the same time. For example, it is possible to display 3D CT images which are used for observing the shape of bone alongside with MRI images

which are used for observing cartilage and internal organs. The software supports cross-section, iso-surface, and volume rendering display methods, as well as any combination of the three. The 3D images are referred to as "volumetric images" or "3D volumetric images", and volume rendering is a rendering (image generation) technique for the effective display of volumetric images. VE can perform high-speed display of 3D images by utilizing Graphic Processing Units (GPUs) for the volume rendering.

2.3 Extracting regions (segmentation)

VE supports the following methods for the extraction of regions (segmentation): "Interactive segmentation", "Region expansion", and "Histogram base" (Fig. 6).

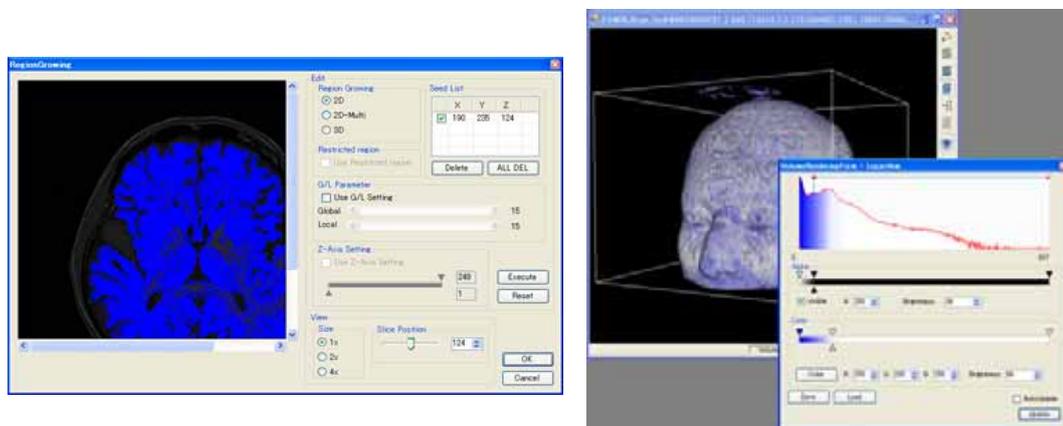


Fig. 6 Segmentation techniques in VE (region expansion (left) and histogram base (right))

2.4 Measuring 3D images

VE supports measurements of lengths, angles, areas, and volumes in 3D images in an interactive manner (Fig. 7). As the capabilities of CT and MRI improve, high-resolution 3D image data becomes available, making it possible to perform high-precision measurements.

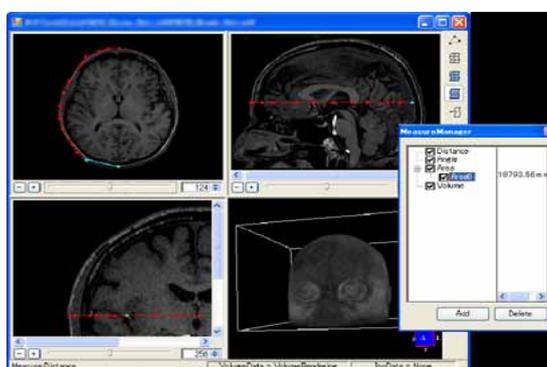


Fig. 7 Measurements performed on a 3D image

2.5 Outputting 3D image and shape data

It is possible to output 3D images and 3D shape models prepared with VE into files. Furthermore, output to the DICOM image format, as well as the STL, DXF, VRML and other shape model formats, is also supported^{b)}. Apart from the construction of actual models, the outputted data can also be used for stress simulations using Finite Element Method (FEM) and preoperative planning.

b) STL, MGF, VRML

STL is an abbreviation of Stereo Lithography, which is a widely used general-purpose format used in rapid prototyping. MFG (Materials and Geometry Format) and VRML (Virtual Reality Modeling Language) are similar data formats for representing polygon shapes, where MGF is used in modeling and visualization, while VRML is popular for web development.

3. 3 Reconstructing 3D shapes

3.1 Preliminary processing

Generally, 3D images (volumetric data) contain areas of noise and other imperfections. For this reason, it is important that these areas are removed at the stage of the 3D image before the conversion into shape data. Furthermore, if imperfections are removed at the segmentation stage when constructing closed surfaces in the case where 3D printers and rapid prototyping devices are used, any subsequent processing becomes simpler. For this reason, VE supports such functions as noise removal, clipping of unnecessary regions, and unification of the brightness of specified regions.

3.2 Constructing iso-surfaces

Specified elements of the volume data which are equipollent and have equal brightness are extracted, and a triangular surface is formed by connecting these elements with adjacent elements (construction of iso-surfaces). Since the constructed surfaces represent polygon data, it is possible to edit them by using the mesh editing function and to output external files for use by other applications. Reduction of the constructed polygon data is then performed by specifying the targets for removal while retaining as many of the features of the shape as possible. Since reduction in the present reduction algorithm is performed in such a way that the removal of polygons does not entail the loss of features, it is possible to perform data reduction while retaining the features of the model.

3.3 Polygon editing function

VE features two polygon editing functions, in one of which users perform editing interactively, and in the other one, the system performs automatic editing. In the interactive mode, the user performs editing by specifying individual vertices, edges, and polygons on the screen. In case the number of

corrected polygons is large, an automatic editing is initially performed, after which the polygons which can not be handled automatically are edited interactively.

3.3.1 Automatic gap repair

Gaps in the model data are automatically found and repaired by adding triangular shapes. Initially, a search is initiated from the vertices of edges of triangles which do not possess neighboring triangles (referred to as "basic vertices" here), and a search for gaps is performed by tracing edges to other basic vertices. After all gaps are automatically extracted, the repaired faces are highlighted, and a confirmation dialogue is displayed.

3.3.2 Automatic rotation

In the automatic rotation mode, a rotation is performed automatically for the purpose of matching the two sides of the polygons. For the purpose of detecting the two sides, adjacent polygons are examined, and the direction of the largest number of normal vectors is adopted. In case the sides of a polygon are incorrectly determined, a correction can be implemented by using the manual rotation function.

3.3.3 Automatic removal

In the model data, clusters of polygons are automatically divided into groups, and removal is performed in units of groups. More specifically, the triangles in the scene are grouped and displayed in a list form. The following two methods can be used for selecting the groups for removal.

Case 1) It is possible to select groups in which the number of triangles is lower than a certain constant. After setting the number of triangles with the threshold slider, the candidate groups are automatically selected.

Case 2) By clicking on the list of groups of triangles, it is possible to switch between individual selective conditions. The selected groups of triangles are highlighted in the main view. Figure 8 represents the result of removing groups of unneeded polygons.

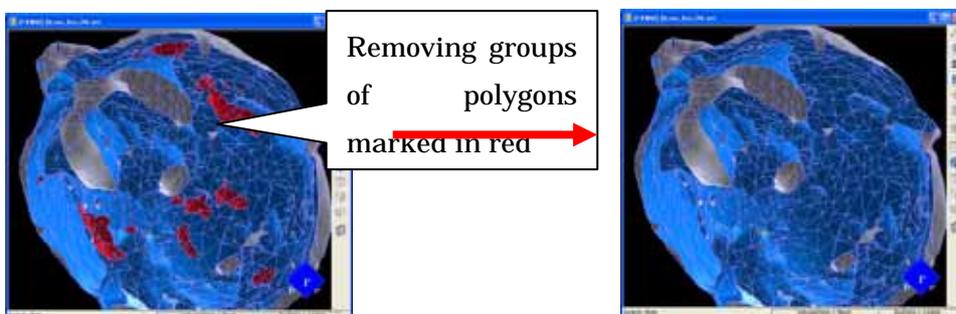


Fig. 8 Automatic removal function

4. Processing sequence

In case bone shape (STL data) is outputted by using a 3D printer or a rapid prototyping device after being extracted from CT and MR images, it is necessary to perform preliminary processing of the image data and posterior processing of the reconstructed polygon data. In general, 3D printers print the lines where the structural data crosses the horizontal surface, thus yielding a structure of stacked layers. For this reason, it is necessary for the cross-sections of the reconstructed shape to be closed, in other words, the line crossing the horizontal surface needs to be continuous in order to prevent contradictions. Although the processing sequence differs depending on the removed part and the modality (CT images, MR images, OCT, ultrasound, SPECT, etc.), in the present paper we present an example of extracting a bone shape and the corresponding processing sequence^[6].

4.1 Processing sequence for shape reconstruction

1) Extraction and editing of the necessary parts

Only the 3D image containing the part for extraction is cut (clipped) from the 3D image obtained by CT or MR imaging. Furthermore, by utilizing relevant editing techniques, any unnecessary areas or areas containing artifacts are removed from the clipped 3D image.

2) Segmentation

By using the classification segmentation function based on histograms, the brightness of all areas apart from those corresponding to the bone is set to a specific value (e.g., zero), thus leaving only the brightness values for the bone. In case the information regarding the internal part of the bone is missing, the area expansion procedure is applied to the outer part of the bone. In this case, multiple seed points (the initiation points for the area expansion) are placed on the outer part of the bone area, and the outer part of the bone area is divided while adjusting the global and local parameters (the parameters which control the degree of area expansion). Alternatively, seed points are placed in the parts whose brightness values represent the bone area, and the continuous bone regions are extracted while at the same time adjusting the parameters.

3) Image filtering and digitalization

The image filter of VE incorporates garbage removal and smoothing functions. In general, the boundary between the cartilage and the bone is not clear, and furthermore, it is necessary to remove the structures corresponding to muscle and tendon. For this purpose, the present function regards the surface of the bone as smooth and presents a clear image of the bone boundary.

4) Image editing

In case it is necessary to close the surface of the clipped image, by using relevant editing functions, the clipped surface is given the same brightness value as that of the extracted bone. If iso-surfaces are generated by applying process 5, the cross-section of the generated surfaces crosses the surface of the bone, thus forming a closed shape.

5) Generation of iso-surfaces

The 3D shape is reconstructed by taking the brightness values representing the bone boundary as iso-surfaces. In case the amount of iso-surface data is too large, the 3D image data is compressed, and either iso-surfaces are generated or the generated iso-surfaces (polygon data) are deleted. Although the processing of compressed 3D data is fast, the surface shape is broken. For this reason, it is possible to generate shapes with higher accuracy if the 3D data is not compressed and the generated iso-surface data is processed with the data removal algorithm.

Figure 9 represents an example of iso-surface generated with the area expansion method on the basis of binary 3D images divided into bone and other areas. The upper surface of the bone is not closed, although it is necessary for the surface to be closed when using a 3D printer or a rapid prototyping device. Although it is possible to utilize shape editing for the purpose of closing the boundary surface, complex shapes require longer manipulation times. For this purpose, the slice image of the boundary surface is colored using a value different from that of the rest of the bone by using the image editing function. Figure 10 represents the result of the generation of iso-surfaces corresponding to the 3D image, in which it is clear that the boundary surface is closed. Furthermore, Fig. 11 represents an example of generated iso-surfaces corresponding to a high-resolution 3D (a 3D image compressed to about 80% of the original image). Although the generation of iso-surfaces in the case where the resolution is high generally requires longer processing times, in the case of VE it is possible to freely change the resolution of the 3D image and subsequently generate iso-surfaces from the low-resolution image.

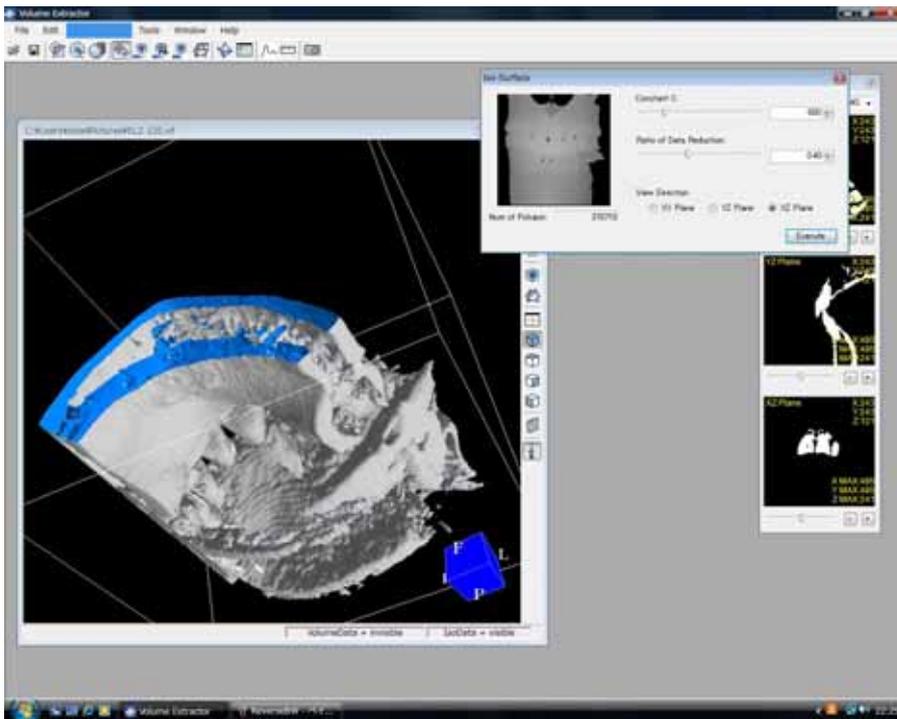


Fig. 9 Segmentation and iso-surface generation by using the area expansion method (Low resolution: 370710 polygons)

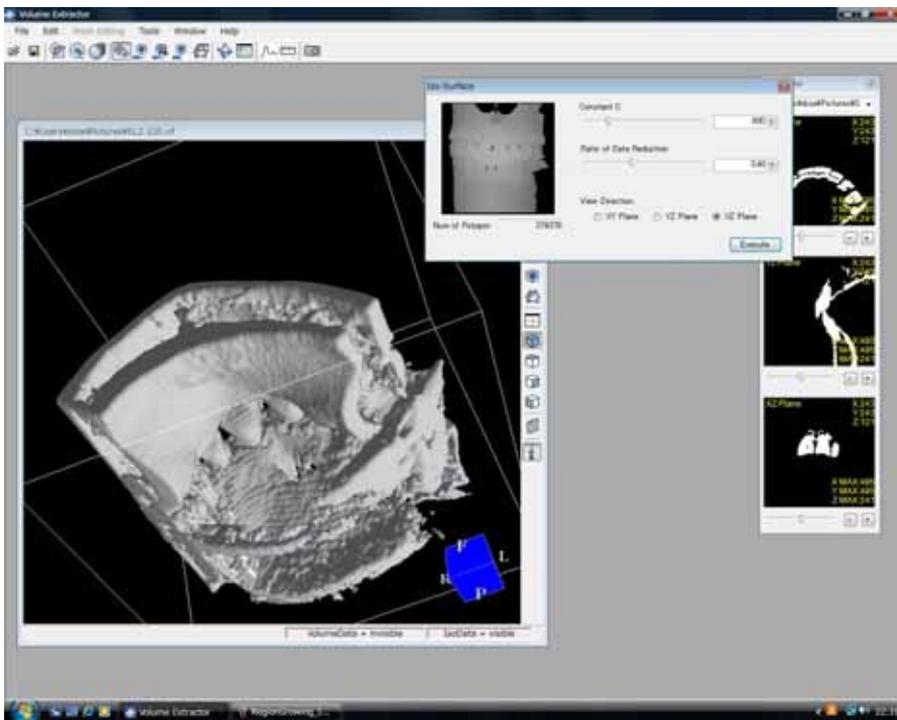


Fig. 10 Generation of iso-surfaces corresponding to the 3D image with closed boundary surface (Low resolution: 374379 polygons)

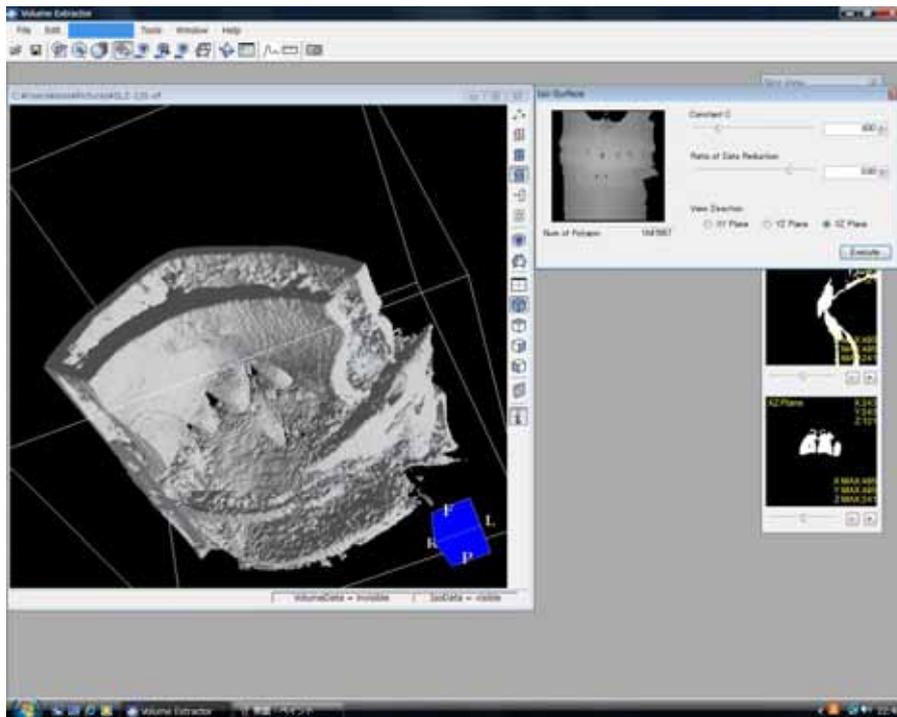


Fig. 11 Generation of iso-surfaces corresponding to the 3D image with closed boundary surface (High resolution: 1647267 polygons)

6) Adjusting the 3D triangular polygon shape

The generated iso-surfaces are subjected to minor adjustments by using the automatic removal function of the mesh editing function, the automatic rotation function, and the automatic group division function. In the case of human CT and MR images, infinitesimal gaps are generated due to noise or in the process of iso-surface generation. For this reason, it is necessary to examine the adjacent edges and automatically repair gaps with small areas. Furthermore, by subsequently using the information regarding the vectors normal to adjacent surfaces, automatic rotation is performed (correction of the inverted surface) in case there are contradictions in the direction of the surface. An outline of the details regarding error handling is provided in Section 4.2. Finally, the entire iso-surface data is spatially divided into groups, and any small groups which are spatially disconnected are automatically removed from the groups attributing to the structure.

4.2 Overview of the error handling in the process of shape editing

In VE, the following errors are defined, retrieved, and repaired. The vertices, edges, and polygons identified as erroneous are displayed in a warning color (e.g., purple).

1) Error of overlapping vertices, edges, and polygons

- Vertex overlap error: indicates vertices whose coordinates overlap
- Edge overlap error: indicates edges composed of the same two vertices
- Polygon overlap error: indicates polygons composed of the same three edges

Overlap errors are retrieved automatically, and elements identified as erroneous are displayed in green, as shown in Fig. 12.

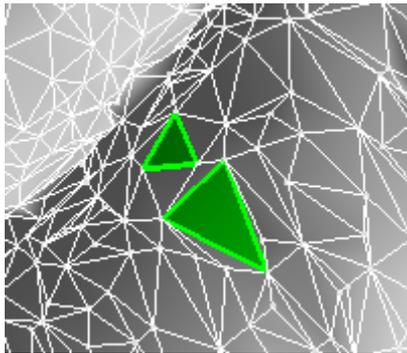


Fig. 12 Displaying a polygon overlap error

2) One vertex - two edges connection error

In a correct model, a search is performed for vertices under the condition that they necessarily connect three or more edges (Fig. 13). Vertices which do not satisfy this condition are marked as erroneous (Fig. 14). Since there are cases in which the polygons containing the offending vertices are located at the margins of the model, it is possible to specify gaps.

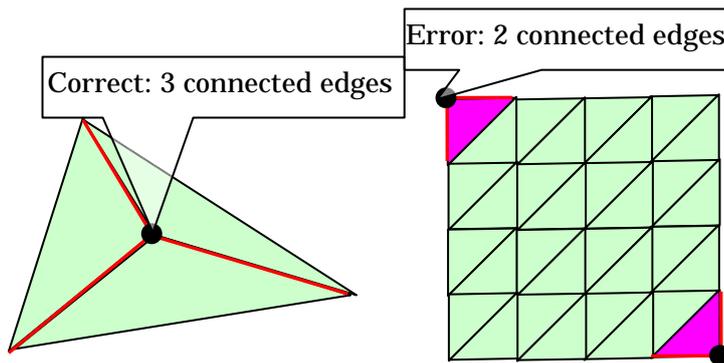


Fig. 13 Number of edges connected to a vertex

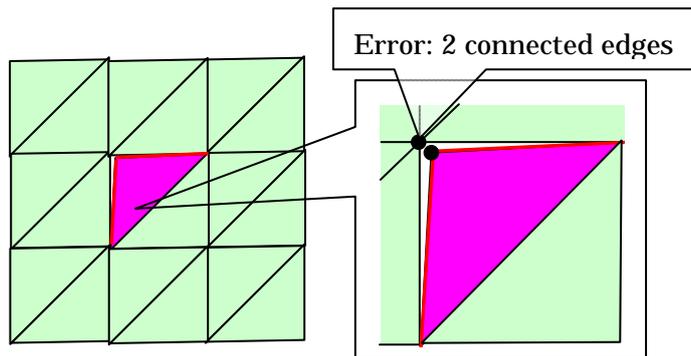


Fig. 14 An example of a vertex connecting two edges

3) One edge - two polygons connection error

In a correct model, a search is performed for edges under the condition that they necessarily connect 2 polygons (Fig. 15). Edges and their corresponding polygons which do not satisfy this condition are marked as erroneous. In case two seemingly adjacent polygons are marked as erroneous, it is considered that they do not share edges. Furthermore, an error is generated in case the edge is shared by three or more polygons. The erroneous polygons can also be seen in parts comprising open edges and gaps.

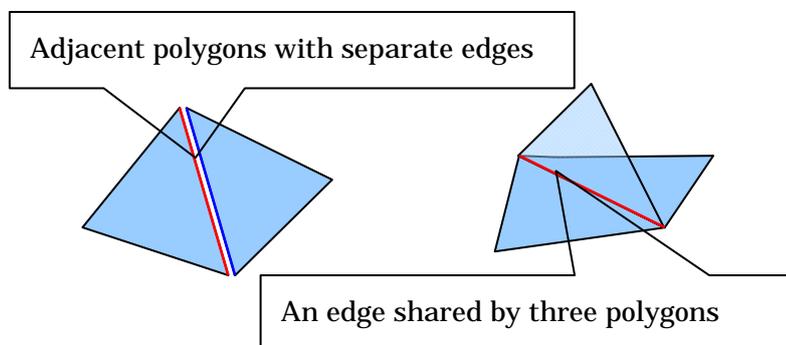


Fig. 15 An example of one edge - two polygons error

4) Normal vector error

Regarding the direction traced by the 3 edges constituting the polygon, the direction of the normal vector is as follows (Fig. 16)

- Counterclockwise: front
- Clockwise: back

Furthermore, if adjacent polygons have the same orientation, the respective directions of the shared edge are opposite with respect to the two polygons. In case the respective directions of an edge shared by two polygons are not opposite, an error is generated (Fig. 17).

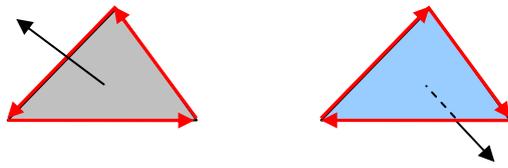


Fig. 16 Edge direction and polygon orientation

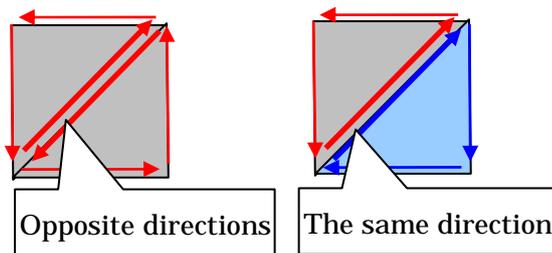


Fig. 17 Using shared edges

Figure 18 represents an example of one edge - two polygons connection errors, and Fig. 19 represents the result from removing the relevant polygons (highlighted in yellow). The result from repairing the gap by using the automatic gap repair function is shown in Fig. 20. Furthermore, Fig. 21 represents the result from correcting the orientation of the generated polygons through the polygon rotation function. The polygons containing the erroneous vertices are removed automatically, and an automatic error search is performed again. Gaps generated in the correction process are repaired either automatically or interactively. Figure 22 represents the result from an automatic search and repair process with respect to normal vector errors.

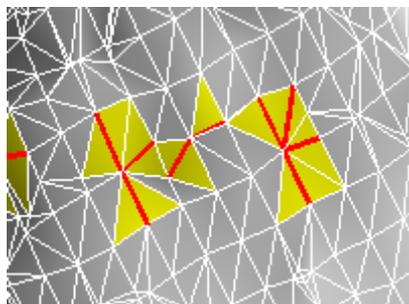


Fig. 18 Displaying one edge - two polygons connection errors

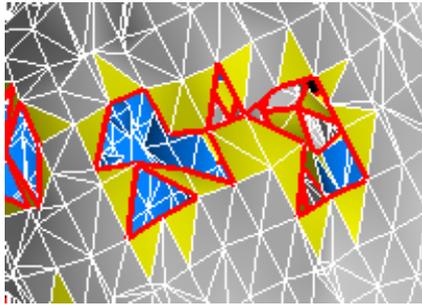


Fig. 19 Repairing one edge - two polygons connection errors

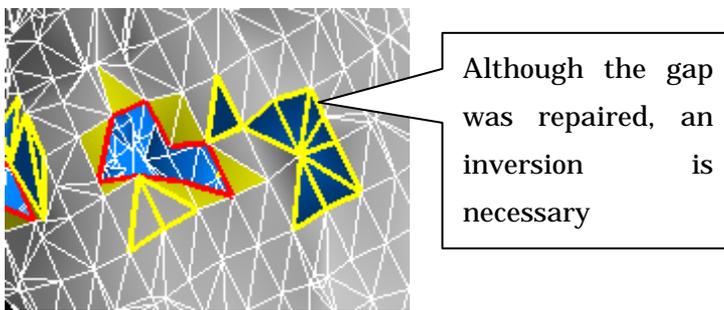


Fig. 20 The result of automatically repairing the gaps once

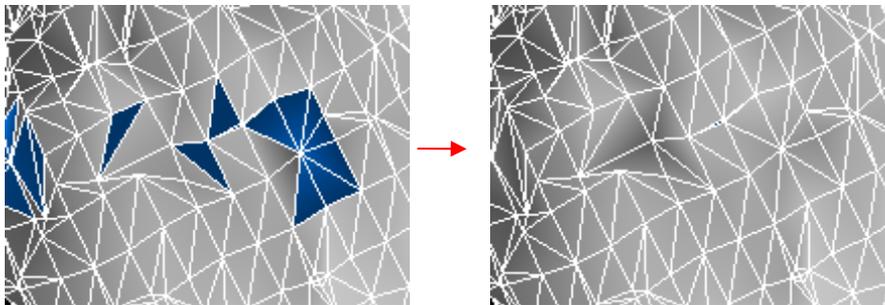


Fig. 21 Rotation after all gaps have been repaired

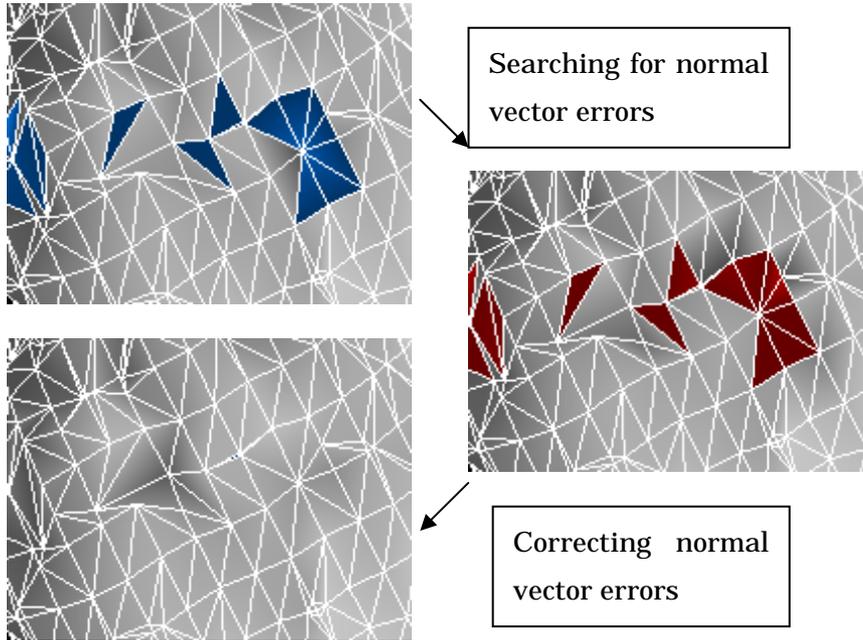


Fig. 22 Searching and correcting normal vector errors

5. Conclusion

The present paper presents an overview of the features of VE Ver. 3.0, with detailed explanation of the concept and the operation of the shape reconstruction functions. VE Ver. 3.0 includes the functions of SMESH Ver. 1.0 and is capable of transforming segmented 3D images (of internal organs, bones, blood vessels, etc.) into triangle polygon data, editing the resulting polygon data, and preparing actual models in a simple manner by utilizing a 3D printer or a rapid prototyping device. The 3D models prepared with the aid of VE can be utilized in many fields of medicine and engineering. For example, shape models containing internal organs, bones, and blood vessels can be used for preoperative planning, operation simulations, medical education, using virtual reality (VR) to obtain informed consent from patients^{c)}, and so on. The plan for future development includes the improvement of the user interface, the implementation of functions such as the ability to add color to the shape data, the ability to create actual models as combinations of internal organs, skeletal structure, and blood vessels, the ability to divide the reconstructed shape into a mesh of tetragons or hexahedrons, and the ability to perform high-speed processing of high-resolution images. A trial version of the present software (Volume Extractor Ver. 3.0 Light 32/64 bit edition) can be downloaded from the home page of i-Plants Systems, Ltd.^[7].

c) VR

VR is an abbreviation of Virtual Reality, which generally represents techniques and systems for generating a virtual world (cyberspace) by using computers and has connections with technology related to computer graphics, networks, voice and touch.

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