Archiving and visualization of the patient's anatomical model using B-spline curve and surface representation

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Abstract— *From the patient's perspective a minimally invasive surgery decreases trauma, the associated pain, and greatly reduces the post-operative recovery time, trauma and faster return to life. It has some disadvantages, like limited field of view and occluded anatomy, which could be overcome by registration of the preoperative patient's anatomical model to the patient's position in the operating room. The aim is archiving and presenting the patient's anatomical model in a manner which is easy to modification and integration into surgical workflow finally causes simplification in perception of operating field. B-spline curve and surface representation for anatomical models were selected. For creating the model from segmentation results, the global surface interpolation algorithm is applied. Scene graph oriented solution was proposed for 3D image data and anatomical model presentation. The whole scene graph is divided into independent branches, which accelerates rendering and simplifies data loading and building the scene graph process. Due to the lack of a "gold standard" for evaluation of the segmentation results obtained automatically, a manual way of correction is feasible. The presented approach was implemented in application for the anatomical liver model presentation using Open Inventor library.*

Keywords: patient's anatomical model, operational field visualization, patient's anatomical model processing, surface visualization

1. Introduction

From the patient's perspective a minimally invasive surgery decreases trauma, the associated pain, and greatly reduces the post-operative recovery time, trauma and faster return to life [1]. In a minimally invasive surgery perception of operating filed is one of the most important factors for successful intervention. Seitel et al. [2] proposed different methods of visualization of needle placement during ablation procedures indicating a significant influence on surgery accuracy. Bartoli et al. [3] indicate five disadvantages of laparoscopic approach: weak depth perception, constrained vantage point, limited field of view, weak haptics and occluded anatomy. There are a lot of efforts to overcome those limitations. Some of them could be overcome by using new hardware techniques as: 3D laparoscopic reconstruction, depth estimation or computer vision approach like Simultaneous Localization and Mapping (SLAM). It is very difficult to integrate a few hardware solutions together (eg stereo camera and flexible head), so the combination of hardware and software solution is used. In the first step, the preoperative patient's anatomical model using 3D medical imaging like Computed Tomography (CT) or Magnetic Resonance (MR) is created. The 3D anatomical model is generated manually, semi-automatically or automatically. Due to the lack of a "gold standard" for evaluation of the segmentation results obtained automatically , a manual way of correction is feasible. After creating the model next important step is registration of of the preoperative patient's anatomical model to the patient's position in the operating room [4]. Due to the absence of unambiguous mapping of coordinate systems during registration, this stage is often divided into two steps: first rigid registration and then deformable registration.

2. Materials and Methods

2.1 Model data and representation

Generally, the patient's anatomical model includes 3D medical images, usually in Digital Imaging and Communications in Medicine (DICOM) format and segmented anatomical structures. The model could be represented as point cloud, polygonal mesh, implicit surface equation or parametric equations [5]. The most common representation is point cloud (eg 3D Slicer [6] and Visualization toolkit [7]). In the presented approach, a parametric representation has been selected due to a few advantages [8]:

- parametric method on the plane can be easily extended to represent arbitrary curve in three-dimensional space,
- parametric curves feature a natural direction of traversal, where ordered sequences of points along a parametric curve can be generated and could be treated as the cross-section of the surface,
- parametric form is more natural for designing and representing shape because curve coefficients have a direct visual interpretation,
- parametric form can represent a surface by introduction of a second parameter.

The volume of stored data is smaller in a parametric representation than in point cloud case because only the net of control points and knots vector should be archived. Generally, B-spline surface $S(u,v)$ is a tensor product of B-spline curve, taking a bidirectional net of control points $P_{i,j}$, two vectors of knots u and v and the products of univariate

B-spline functions [8]:

$$S(u,v) = \sum_{i=0}^{m} \sum_{j=0}^{n} N_{i,p}(u) N_{j,q}(v) P_{i,j}, \qquad (1)$$

where $N_{i,p}(u), N_{j,q}(v)$ denote B-spline basic functions. In the presented approach cubic B-spline functions are used $(N_{i,p}(u) = N_{i,4}, N_{j,q}(v) = N_{j,4})$.

2.2 Model creation

Anatomical model usually represents the surface of segmented structures. As regards surface fitting algorithm for labelled segmentation volume there are two approaches: approximation and interpolation [9]. In the interpolation case, which is used in the presented approach, a surface which passes directly through a given net of data points $D_{c,d}$ is constructed. All data points, which are necessary input data for interpolation algorithm, are found at the boundaries of a segmented region. Boundaries of a segmented region which is represented as a volumetric binary mask are found using Moore-Neighobor Tracing algorithm modified by Jacob's stopping criteria [10]. After finding, boundary points are treated as input data. The number of selected points depends on interpolated shape (eg for liver surface forty points for DICOM slice are used) and this is a compromise between model size and its accuracy. Vectors of knots are found assuming a uniform distribution of knots. To find unknown spline curve coefficients, surface global interpolation algorithm is calculated [9]. Surface global interpolation algorithm can be regarded as a generalization of curve fitting interpolation algorithm, which allows to find the curve of degree d passing through a set of points D_c in the order given. For the given net of data points $D_{c,d}$ and values of parameters $u = s_c$ and $v = t_d$ the corresponding data point satisfies the equation of the surface:

$$D_{c,d} = S(s_c, t_d) = \sum_{i=0}^{m} \sum_{j=0}^{n} N_{i,p}(s_c) N_{j,q}(t_d) P_{i,j}. \qquad (2)$$

The input of the algorithm are net of data points, two knots vector and degree of B-spline curves. For fitting surface given a grid of $(m+1) \times (n+1)$ data points Dij ($0 \le i \le m$ and $0 \le j \le n$) and a degree (p,q), allows to find a B-spline surface of degree (p,q) defined by $(m+1) \times (n+1)$ control points that passes all data points in the given order. Surface interpolation algorithm has been used to find liver surface and curve interpolation algorithm for central lines of segmented vessels respectively.

2.3 Visualization application architecture

The main challenge for the imaging navigation system is presentation of a real-time model of the operating field, which comprises: a personalized model of the patient's anatomy, models of operational tools, additional components to facilitate an orientation in the space (coordinate system
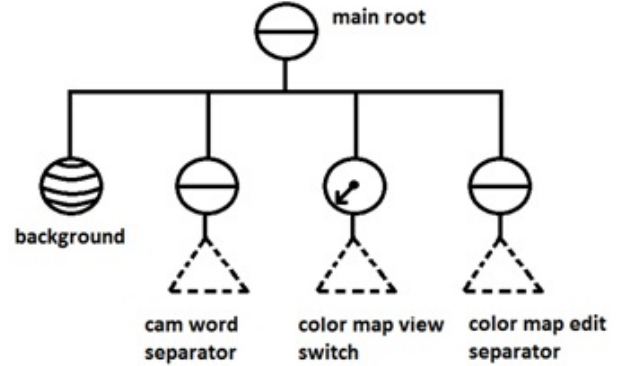

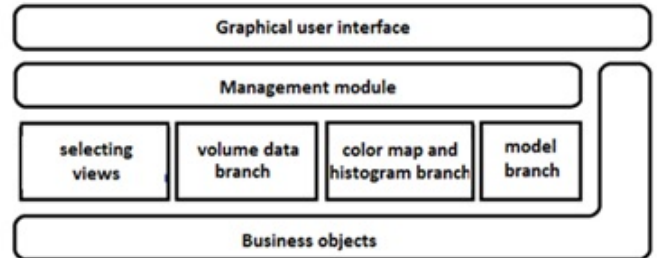Fig. 1: Division of main scene graph in independent sub-branches

Fig. 2: Application architecture modules

orientation, volume data histogram, bounding boxes of the anatomical models, etc). Another important problem is how to store the data in a video card pipeline, mainly because of the size of personalized model. The most commonly used solution is scene graph [11], where the data objects in the rendering pipeline are represented only once in the graph and connected with references. The graphics engine renders the scene using recursive references while bypassing graph objects. Because of the need for real-time rendering, scene graph division is proposed to store individual components as independent scene graph sub-branches (cf. Fig. 1). Scene graph is presented in the figures in the form of the nodes with function description.

Application architecture (cf. Fig. 2) is based on a component approach [12], where graphical user interface includes scene graph viewer, management module encapsulates root of scene graph and represents interface of scene graph to the other application components. Every sub-branch of scene graph is implemented as a separate component.

The management module accepts commands from the user interface and triggers an appropriate events in the scene graph. It also takes care of creating the correct scene graph from loaded data. It includes classes responsible for the synchronization between the volumetric model (DICOM data), a model composed of the curves (boundaries of segmented
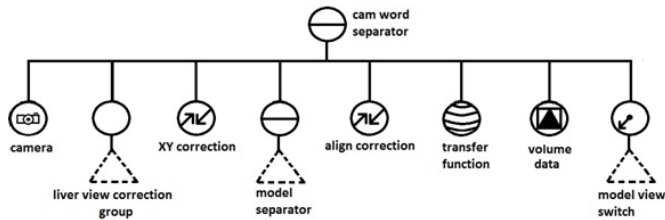
Fig. 3: Scene graph volume data branch

anatomical structures).

The colour map and the histogram components are responsible for enabling the user to change the colour to represent the voxels values that make up the volumetric image. Histogram presents a group of voxels of the same value in the entire volume data.

The selecting views component is responsible for providing functionality that allows the user to select a presentation manner, such as clipping volumetric model display, presenting it as a cross-section, or presenting the whole scene graph. Nodes in this module which are related to the editing mode, will be described in the next paragraphs.

In order to avoid unnecessary complexity in building a scene graph, the responsibility for its construction was divided into individual modules. This will allow the gradual creation, depending on the data being read with your selections, and the integration will take place in the layer of management.

2.3.1 Visualization Volume data

The sub-branch responsible for displaying volumetric data consists mainly of volume data node (cf. Fig. 3) which represents DICOM image data in the form of three-dimensional texture. Presenting manner of volume data depends on the selected visualization mode (cf. Fig. 4).

2.3.2 Visualization anatomical models

The model is presented in the form of spline curves. The main separator contains as many child nodes as many curves exist in the loaded model (cf. Fig. 5). Each curve defines the colour by which it is represented ("material" node) , then a special node that stores the control points and knots appropriate to display curves ("coordinates" node).

For each curve a separator node is defined that holds the points that appear on the screen, which allows a user to edit interactively the coordinates of the selected control point, by selecting and moving it (cf. Fig. 6). The single control point is represented as a sphere node, manipulator and sensor. The manipulator is presented as a cube. The manipulator movement is detected by the associated sensor and it updates the previous position ("delta translation" node). The translation shall be placed before the ball, causing it to move in sync with the manipulator.
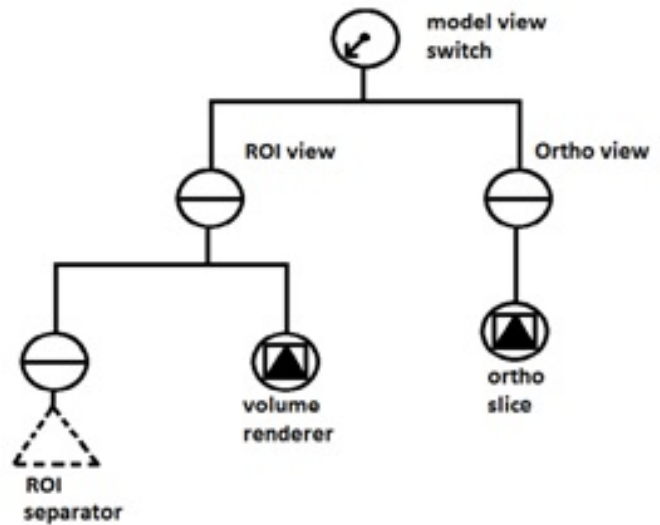

Fig. 4: Switching visualization mode of volume data

3. Experiments and evaluation

The presented approach was implemented in the application for anatomical liver model presentation using Open Inventor library [11] and have been evaluated using the data set consisted of twenty abdominal CT obtained from the Department of Clinical Radiology of Silesian Medical University. The graphical user interface is presented in the next figures (cf. Fig. 7, 8), where selected structures: liver surface and vessels, are presented in green colour against DICOM data presented in a grey-scale map. The whole model of the liver and tumours or selected cross-section could be presented against DICOM data and a manual correction is possible.

In general, the model verification process is a complex issue. All selected and segmented structures should be validated separately. To simplify this process, the advantages of the parametric model representation is applied. As mentioned earlier, cubic spline curves are used which are characterized by the local control property. Moving the control point corresponding to the B-spline curve segment will only affect three local segments, which propagate shape changes to adjacent cross-sections (cf. Fig. 7). The individual segments of vascular structures are represented in the form of spline curves. The verification of results takes place in the volumetric visualization mode due to the variation in the direction of the vessels (cf. Fig. 8). It is also possible to insert additional control points into the curve if necessary. The verified anatomical model could be stored in data files.

4. Discussion and Conclusion

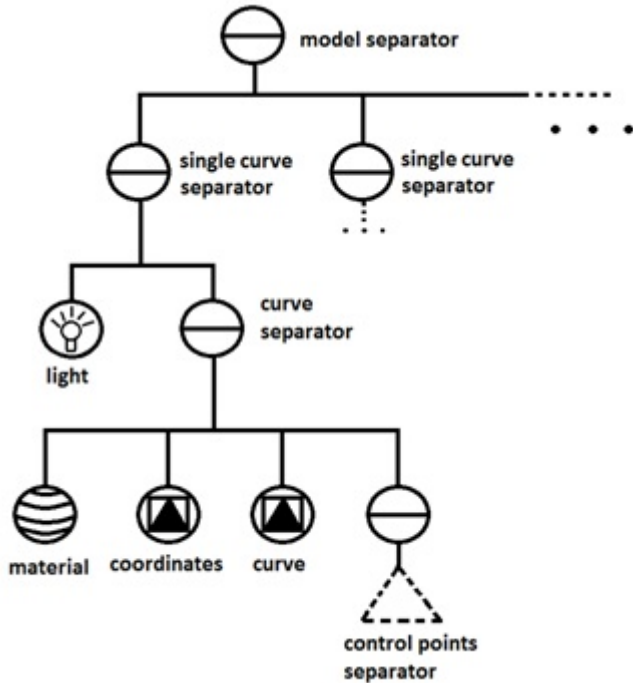Representing an anatomical model in parametric curve and surface is useful. From archiving point of view it takes a

Fig. 5: Scene graph branch for model visualization

Fig. 6: Scene graph branch for manual curve correction

smaller place because it is not necessary to keep all surface point positions but only control points and knots vectors. From the presentation point of view, control points have important properties, so that moving them influence only the local segments. Smoothness of B-spline curves, depending on basic functions degree, could be applied to model anatomical shapes which are usually smooth. Additionally, the curve is included in a convex polygon stretched at control points. Visualizing control points and making them dragable make the whole curve dragable.

Parametric representation is more powerful for data traversal, finding cross-section, etc.. It is also possible to change internal representation of spline curve and surface from weighted form of B-spline basic function for pp-form [13], which is based on derivative matrix and is more effective for computation. Using the procedure for inserting a node parametric representation could be treated as a quasi multi-resolution model which could interpolate shape more precisely by inserting an additional segments. To fit more difficult shape it is also possible to change B-spline basic function degree.

The scene graph is useful technique for anatomical model presentation. Basically, it collect all rendering objects in an effective way, but using more mature implementation could be connected with collision detection module and notifies the collision occurrence of a surgical tool and important anatomical structures. The division of scene graph into independent branches (implementation of "divide and conquerâĂİ paradigm) and introduction of management module
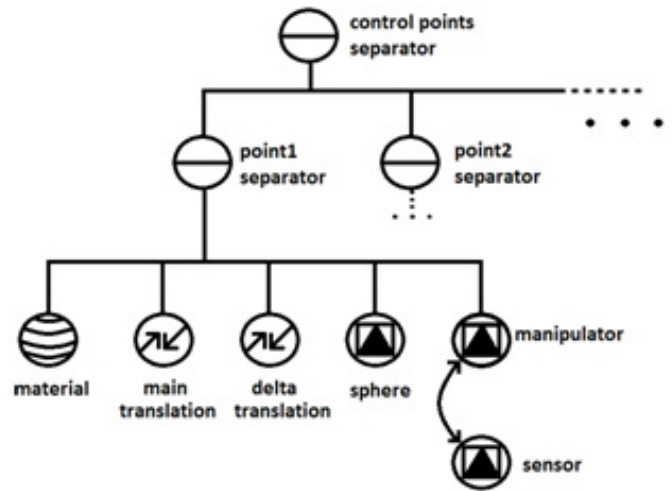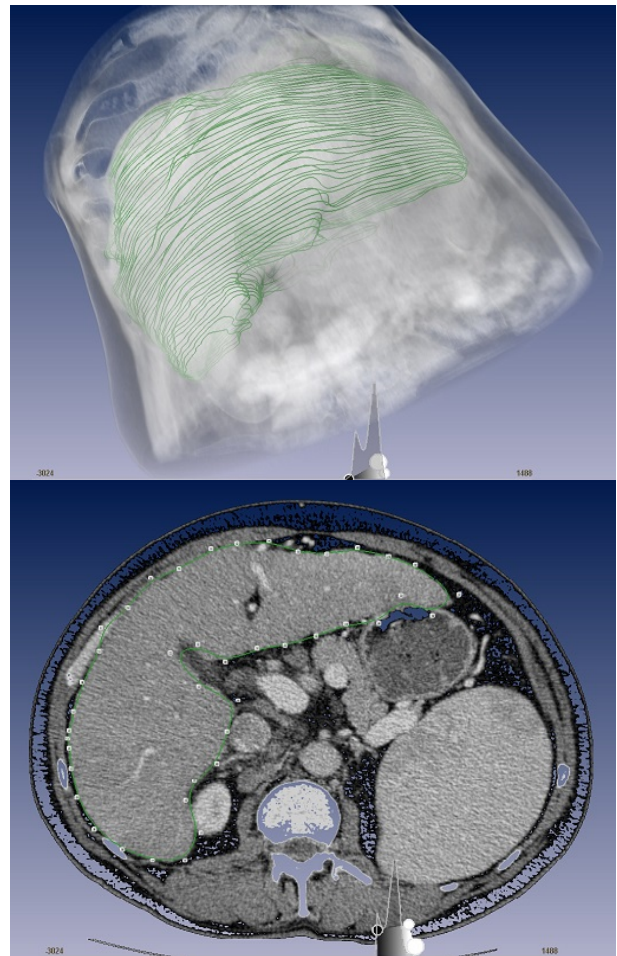

Fig. 7: Liver surface model representing as set of B-spline curves (up), and control points for selected curve for manual correction (down).
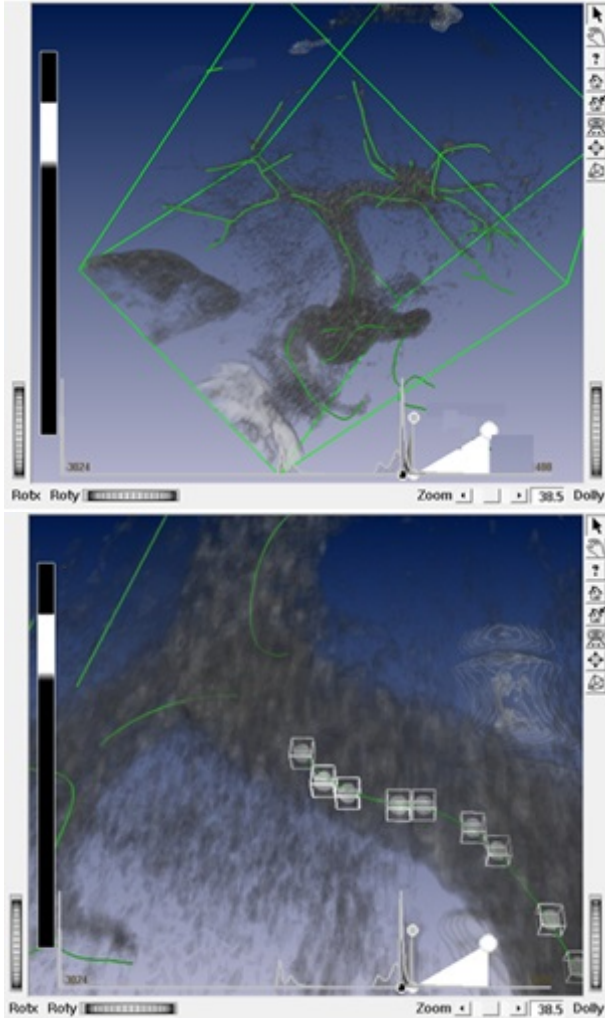
Fig. 8: Liver vessels model representing as set of B-spline curves (up), and control points for selected curve for manual correction (down).

simplify the integration of this technique for different clinical cases even for rendering sophisticated scenes.

From the global point of view usefulness of patient's anatomical model depends on the proper use in surgical workflow. To avoid mistakes, a close cooperation between the radiologist and surgeon is desirable. After manual correction of automated generated model in a planning phase, possible intervention techniques, are easier to compare (by selecting a target an an entry points and tracing the possible surgical tools trajectories). After an initial registration of the preoperative model and patient physical position, anatomical model could be useful during interventions. Parametric representation simplifies presentation only selected part of the model. In some planning intervention methodology key frame of DICOM slice is selected (eg frame corresponding to diaphragm position) to take into account deformation of anatomical structures [14] caused by breathing or emphasis

of laparoscopic instruments [15]. The values of B-spline model parameter for corresponding cross-section could be stored and the ability to visualize specific cross-section of the model is desirable.

5. Acknowledgment

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