

Model-based segmentation

For treatment planning with Pinnacle³

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Introduction

Organ delineation accounts for a significant amount of the time required for radiation therapy treatment planning. Manual, slice-by-slice contouring of organs on CT images is time consuming, tiring, and can take several hours of valuable clinician time for a single plan. Contouring time dramatically increases with the clinical implementation of intensity modulated radiation therapy (IMRT) and image guided radiation therapy (IGRT) techniques.

Version 8.0 of the Philips Pinnacle³ planning system introduces model-based segmentation (MBS), an automated organ delineation module that greatly increases contouring efficiency. Using MBS, an organ model is first positioned over the anatomical structure in the image set. A deformable model algorithm then adapts the organ model to the boundaries of the anatomical structure. 3D editing tools are available to allow additional manipulation of the model.

Organ model shapes

To model an organ's shape, the algorithm uses a triangular surface mesh. The initial mesh is generated from standard Pinnacle³ contours using a curvature-guided triangulation algorithm. The algorithm

produces a higher concentration of triangles in areas of high detail (high surface curvature) and a smaller number in areas of low detail.

The quality of an organ model is improved if shapes from several patients are combined to produce an average mesh, also known as a mean mesh. All patient samples added to the mean mesh are given equal weights, so as the number of samples increases the influence of each individual sample decreases. Five to ten samples are usually sufficient to generate a mean mesh. MBS provides an initial library of organ models as well as tools to add, delete, modify, and group them.



Surface meshes for brain (left) and mandible (right) models.

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Organ model adaptation

Position the mesh

The first step in the segmentation process is to position the mesh over the organ of interest in the image set. 3D tools are available to translate, scale, and rotate the mesh. An additional 3D editing tool pulls all mesh vertices that are within a user-specified distance of the mouse location. The tool displaces vertices in the direction of the mouse motion, where the displacement decreases with increasing distance between the mouse position and the vertices according to a Gaussian function.

Organ models are saved in the supine position and head-first orientation. When a model is loaded, it is automatically oriented to the current patient position (supine, prone, left, or right) and orientation (head-first or feet-first). This allows the use of a single model for patients in different treatment positions.

Automatic adaptation

The second step is the automatic adaptation of the triangular surface mesh. The adaptation of the mesh is an iterative optimization procedure. It minimizes the energy in a system given by the weighted sum of its internal energy E_{int} (characterized by the mesh shape), and its external energy E_{ext} (characterized by image feature points which potentially lie on the surface of the anatomical structure in the image). The total energy E_{total} in the system is given by:

$$E_{total} = w_{int} E_{int} + E_{ext}$$

where w_{int} is the relative weight of the internal energy with respect to the external energy, and is inversely related to the flexibility of the organ. Smaller w_{int} values are used for organs with significant shape variability across subjects, such as the bladder. Larger w_{int} values are appropriate for organs with less shape variability, such as the femur. Ten iterations are performed during an organ adaptation. The internal and external energies are computed at each iteration and used to build a linear system of equations that is solved to produce a new mesh shape. Multiple adaptations may be performed sequentially.

Internal and external energies

The internal energy is computed by summing, over all triangle edge vectors, the difference between the corresponding edge vectors in the transformed organ model mean mesh and the current surface mesh and is given by:

$$E_{int} = \sum_{e=1}^{N_{edges}} \left(\vec{x}_e - T\vec{x}_e^m \right)^2$$

where N_{edges} is the number of triangle edges, \vec{x}_e and \vec{x}_e^m are corresponding edge vectors in the current surface mesh and the mean mesh (respectively), and T represents the rigid-body transformation matrix that registers the mean mesh to the surface mesh. T is determined using a point-based registration between the vertices of both meshes.

The external energy is computed by searching for feature points in the image set. These are points meeting a set of rules describing the specific appearance of an object's surface in images of a specific imaging modality. To find these points, a feature search is performed along the normal vector of each triangle of the mesh. The image gradient is evaluated every 0.1 cm, from 1 cm inside the surface mesh to 1 cm outside. The point that is chosen to be most likely on the surface of the object of interest is the one that satisfies a combination of rules based on the image gradient vector and the proximity of the point to the surface mesh. A relative weight is assigned to it according to the magnitude of the gradient and the component of the gradient vector in the direction of the triangle normal. The external energy is then given by:

$$E_{ext} = \sum_{t=1}^{N_{triangles}} w_t \left(\vec{u}_t \sum \left(\vec{x}_t^f - \vec{x}_t^c \right) \right)^2$$

where $N_{triangles}$ is the number of triangles in the mesh, w_t is the feature's relative weight, \vec{u}_t is the unit vector pointing in the gradient direction at the feature location, \vec{x}_t^f is the spatial coordinate of the feature, and \vec{x}_t^c is the spatial coordinate of the triangle center. This form of external energy allows the mesh vertices to move along the surface orthogonal to the gradient direction at the feature point, which increases the robustness of the adaptation.

Feature search parameters

An MBS adaptation uses a combination of rules intended to characterize the boundaries between the organ and the adjacent structures. These rules drive the detection of image feature points along the normal vector of each triangle. Image feature points within the search range that match these rules drive the adaptation of the surface mesh.

The following user-selectable parameters are used to evaluate potential features.

Minimum and maximum CT value

Disregard a point from the feature search if its gray value is outside a minimum or maximum range. This allows you to quickly reject false features.

Gradient direction

The adaptation algorithm can look for positive or negative gradients. A positive gradient direction corresponds to organs that appear darker than the surrounding structures, such as the lungs. A negative gradient corresponds to organs that appear brighter than the surrounding structures, such as bones. When the gradient at a point being evaluated as a potential feature is in the wrong direction, the potential feature influence is minimized by assigning it a low weight. The algorithm can also look for unsigned gradients, in which case large gradients in either direction are assigned high weights.

Maximum gradient

The maximum gradient value can be used to reject points where the gradient is greater than the maximum value. Alternatively, the feature weight can be damped when the gradient is greater than the maximum gradient such that the influence of the feature does not keep increasing with increasing gradient. This is useful when searching for tissue-tissue boundaries where gradients are small, instead of tissue-air or tissue-bone boundaries.

Gradient clipping

When soft clipping is selected, points at which the gradient is greater than the maximum gradient will be considered features whose relative weight decreases monotonically as the gradient in the image set increases. The relative weight of a feature also depends on the three components of the gradient in the image set. When hard clipping is selected, points at which the gradient is greater than the maximum gradient are not considered features and are ignored during the search along the triangle normal vector. When the gradient is less than the maximum gradient, the relative weight of a feature depends only on the component of the gradient in the image set that is parallel to the triangle normal vector.

Regions to avoid

The adaptation algorithm can avoid points where the gray values are within a specified range, or that overlap with a specified region of interest. When such points are found within the mesh, the mesh is forced to avoid those regions by constraining the solution of the system of equations defined by E_{total} to place the overlapping vertices on the edge of the region to avoid.

Proximity weight

The proximity weight controls the relative importance of features detected at various distances from the mesh. This parameter can be used to prevent the model from attracting to features that are far away from the mesh. A higher proximity weight gives more importance to features that are closer to the mesh.

Limit feature search

The limit feature search option is used during the feature search process to prevent the mesh from being attracted to false features. When the system evaluates a specified number of consecutive potential feature points without finding a feature in the minimum or maximum CT value range, the search along the normal vector for that particular triangle stops immediately and the system moves on to the next triangle. When the gray values inside the organ are all valid, evaluating a number of consecutive steps without finding a valid feature indicates that the system is currently searching for features outside the organ. Any feature found beyond that point must therefore be a false feature and should be rejected.

Manual editing

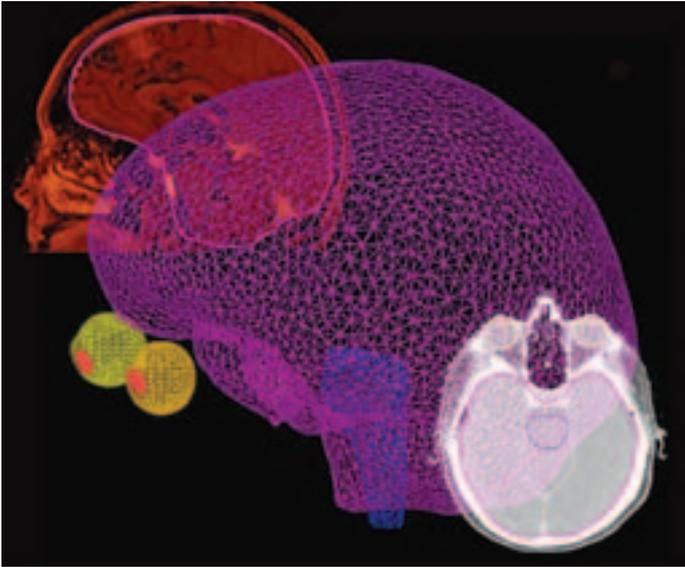
It may be necessary to edit the mesh if the automatic adaptation procedure does not provide the desired accuracy due to attraction to false boundaries, poor model initialization, or weak image feature response at the correct locations. A 3D Gaussian editing tool may be used to quickly reshape the mesh. An algorithm is available to smooth the mesh, as well as a feature that allows you to undo or redo the last mesh manipulation.

It is possible to load and shape a mesh using only the manual 3D editing tools instead of performing adaptation. This is useful for creating dose-shaping structures for IMRT planning.

When the mesh for a given organ has been correctly defined, the mesh is converted to the Pinnacle³ contour format for planning. The standard contour editing tools may be used at this point to modify the region of interest.

Using MBS for 4D image data

A single plan may be based on multiple image sets (MRI, inhale and exhale CT, or 4D CT). MBS allows propagation of a mesh from primary to secondary image sets, or vice versa. Once the mesh has been propagated, it can be manually positioned or adapted on the new image set(s).



Brain, brainstem, eye, and lens models propagated from CT to MR image set

Summary

The Pinnacle³ MBS module supports automated organ delineation through the use of organ models represented by 3D surface meshes. The models are manually positioned in an image set and then automatically adapted to the boundaries of the anatomic regions of interest. 3D editing tools allow manual correction of adaptation results and efficient creation and manipulation of standardized dose-shaping contours for IMRT planning.

Further reading

For further information on model-based segmentation, please refer to the following publications.

T. McInerney and D. Terzopoulos. "Deformable Models in Medical Image Analysis: A Survey." *Medical Image Analysis*, 1(2), 91-108, 1996.

J. Weese, MR. Kaus, C. Lorenz *et al.* "Shape constrained deformable models for 3D medical image segmentation." In Insana MF, Leahy RM, editors. *Information Processing in Medical Imaging*. Lecture Notes in Computer Science. Los Angeles: Springer, Vol. 2082, 380-387, 2001.

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V. Pekar, TR. McNutt and MR. Kaus. "Automated model-based organ delineation for radiotherapy planning in prostatic region." *International Journal of Radiation Oncology Biology Physics*. 60(3), 973-980, 2004, 61(2), 635, 2005. (erratum).



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