Image Segmentation Using MRI Vertebral Cross-Sections

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ABSTRACT

Computer Assisted Spinal Surgery requires the development of a 3-D image of a patient's spine. A method is being developed to construct such a 3-D spinal image from axial MRI cross-sections, using a deformable template. This paper outlines techniques used to register the model with the patient data. First an algorithm based on symmetry of the anatomy is developed to determine the position and orientation of the vertebrae in each cross-section. Second, an active contour is used for segmentation of the spinal cord. Last, a novel edge detection scheme is developed to identify the low contrast edges of the vertebral body in each cross-section.

1. INTRODUCTION

The current technology used in orthopedic surgery is based on an X-ray model of the spine for pre-operative planning. In order to obtain the high-resolution volumetric data required for a satisfactory spinal model using X-ray CT the patient and the medical staff must be subjected to a significant X-ray dose, which may result in ill side effects. Magnetic resonance does not have any known serious side effects. The primary obstacle in substituting MRI for CT lies in the physics of the imaging modalities [1]. X-ray imaging presents an attenuation map of the intervening material, providing high contrast of bone, which has a relatively high density. Conversely, magnetic resonance relies on proton spin and favours soft tissue; bone appears as low intensity shadows having low contrast with surrounding tissue [4].

The ultimate vision for this project is a spinal modeling system for computer-assisted spinal surgery that uses MRI, thereby providing the accuracy required for operative success without the substantial patient radiation dose characteristic of current X-ray systems.

1.1 Approach

Due to the poor bone contrast inherent in MR images, it is not feasible to accurately segment vertebral sections in each MR slice independently [4]. The goal of this research is to exploit the correlation between the image structure of adjacent slices. Specifically, a 3-D deformable model of the spine is to be used as a predictive guide for edge detection processes.

Registration of the 3-D model with the 2-D slices requires that the vertebrae in each slice be normalised with respect to position, orientation and scale. Also, salient landmarks are required to anchor the model to the patient data. Section 2 of this paper describes the methods used to determine the position and orientation of the vertebra in each slice. Section 3 discusses an active contour approach for segmentation of the spinal cord, which will act as a landmark. Section 4 will outline a novel edge detection technique used for the vertebral body boundary, which is used to estimate scale. Finally, the future directions of this research will be discussed in the concluding section.

1.2 Data Set

Researchers at the University of Calgary provided the data sets used in this research. The data sets include a series of axial MR and X-ray CT images of the lumbar spine.

2. TRANSLATION AND ORIENTATION

Since the MR slices are not in accurate alignment necessary for 3-d reconstruction, the following procedure translates and orients the slices to achieve accurate alignment.

2.1 Spinal Cord Position

The near symmetry characteristic of the human body was exploited in finding the position of the vertebra in each image. Specifically, the horizontal co-ordinate of the

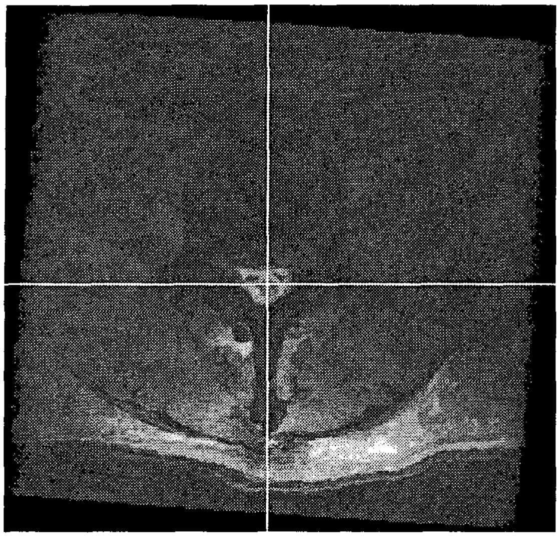

Figure 1 - MR Image with detected spinal cord centre and corrected orientation

spinal cord position was determined by estimating the axis of symmetry. Each slice was "folded" over a vertical line that was scanned across the image. The fold line that resulted in the minimum mean squared error between the faces of the folded image was deemed the axis of vertical symmetry, and therefore the horizontal centre of the vertebra.

The feature used to resolve the vertical displacement within each image is the spinal cord. Its position is determined by minimising mean squared error of a spinal cord template scanned down the axis of symmetry.

This method proved very reliable in determining accurate estimates of the location of the spinal cord in all cross-sectional images.

2.2 Vertebral Rotation

The symmetry approach was again applied to measure the rotational offset. This was accomplished by centering the vertebrae in the slices and incrementally rotating the symmetry axis about the spinal cord. The rotated images were again "folded" and the MSE criterion between the two resultant images was minimised. The orientation of each image could then corrected by applying the opposite rotational offset. This algorithm yielded consistent improvements to the alignment of the vertebrae with the image axis.

It was noted, however, that the success of the rotational offset detection algorithm is dependent on an accurate centre of rotation. Correspondingly, the success in determining the vertical symmetry axis is dependent on reliable rotational correction. As such, an iterative loop consisting of repeated centre detection and rotation correction was implemented and results were improved further. Figure 1 shows a typical result of the rotational correction. Also, the intersection of the horizontal and vertical lines indicates the identified centre of the spinal cord.

3. LANDMARKING

In order to register a spinal model to patient cross sections, a set of image landmarks must be identified. These landmarks are used to fix the model to the patient data longitudinally. As such, appropriate landmarks must be accurately identifiable, and clearly resolve location along the length of the spine.

3.1 Spinal Cord Segmentation

The spinal cord was chosen as an appropriate set of landmarks for two reasons. First, the MRI contrast at the boundary of the spinal cord is relatively strong, which should enable accurate edge detection for all cross-sections. Second, the size and shape of the cross-sections of the spinal cord change in a somewhat predictable fashion along the length of the spine. Aggregating the spinal cord boundaries in each cross-section into a 3-D volume will provide a suitable structure to register the spinal model.

One practical advantage to the selection of the spinal cord as a landmark feature is that from the method described in Section 2, the centre point of the spinal cord can be readily identified. Consequently, the segmentation task is able to disregard most of each image except for a small sub-image that is known to contain the spinal cord. This eliminates many image features whose boundary edges are stronger than the spinal cord boundary edges.

3.1.1 Edge Detection - Initial Attempts

Initial edge detection attempts were done using a canny edge detection scheme. Due to strong edges within the spinal cord, the canny edge detector was not able to uniquely identify the boundary edges of the spinal cord. Also, in many cross-sectional images, there is a large variability of edge strengths along the spinal cord boundary. Accordingly, the edge detection was unable to detect a complete boundary contour of the spinal cord in such images.

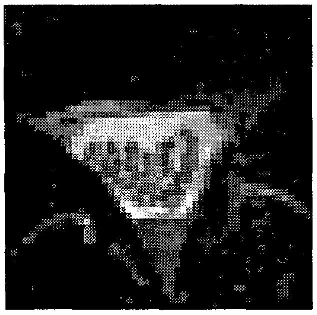

Figure 2a - Original spinal cord sub-image

Figure 2b - Result of Canny edge detection

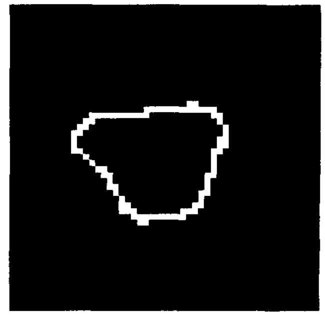

Figure 2c - Result of active contour algorithm

3.1.2 Active Contours

In order to achieve a complete boundary edge, an active contour approach to edge detection was implemented [3]. The basic idea of this approach is to identify the path of greatest edge strength that completely encircles the identified centre of the spinal cord.

The active contour (or "snake") is defined by a set of anchor points and the linear interpolations between successive pairs of these points. The anchor points are defined on an angle and radial length co-ordinate system, where the centre of the spinal cord is the origin. The angle component for each point is fixed, so that the points are equally spaced in angle from 0 deg. to 360 deg. The radial lengths of the anchor points are variable and are the defining parameters that are adjusted in the optimisation procedure.

The optimisation procedure for the active contour is as follows:

1. **Measure the edge strength** at each pixel of the sub-image according to a gradient magnitude.
2. **Initialise the anchor points**. This is described in more detail below.
3. **Adjust the radial length of one anchor point**. For each possible length, determine the resultant snake and evaluate according to the correlation between the snake and the edge strength image. Find the radial length that maximises this criterion given that the radii of the other anchor points are fixed.
4. **Repeat** step 3 for the next anchor point. Continue to adjust the anchor points until no improvements can be made. That is, for each anchor point the evaluation of the entire contour can not be improved by adjusting its radial length.

A critical factor for the success of this algorithm is the number of anchor points used to define the contour. If too few anchor points are used, then with the simple linear interpolation, the contour is unable to deform to the small details of the boundary edge. If too many anchor points are used, then a large adjustment to a single point will produce a sharp spike in the contour, which will reduce the correlation evaluation criterion. As a result, significant changes to the contour can not occur, and its performance is more greatly dependent on the initialisation of the anchor points.

To account for these considerations, our algorithm iteratively increases the number of anchor points. Initially, a contour is found using 8 anchor points. This contour can not account for small details in the boundary, but does provide a sufficient approximation of the spinal cord to be used to initialize a more powerful active contour. For the next iteration, the number of anchor points is doubled to 16. These points are initialized to points along the first contour. From this initialization, it was assumed that each anchor point is near the true boundary, but the contour can now achieve greater precision. The number of anchor points is similarly increased until there are 64, which provides sufficiently accurate contours for this application.

Figure 2c) shows the final contour for the spinal cord using 64 anchor points. For comparison, figure 2b) shows the result of the canny edge detection for the same sub-image (Figure 2a).

4. SCALE ESTIMATION

Finally, to register a spinal template to the patient data, a method is needed to determine the scale of the patient spine, so the model can be deformed accordingly. To do this scale estimation, it is necessary to identify the boundary of the vertebral body.

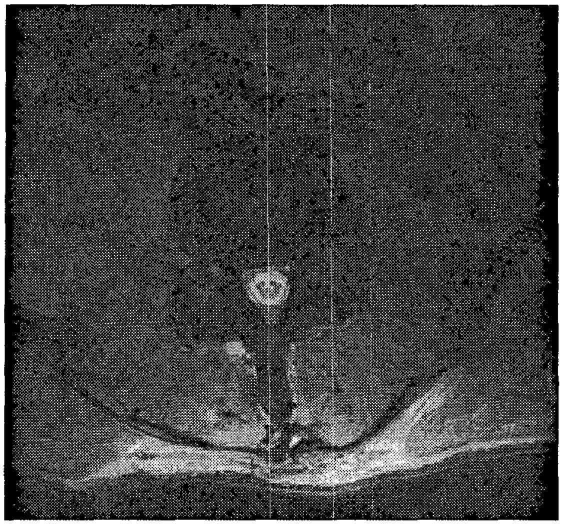

Figure 3a) Original spinal MR cross-section

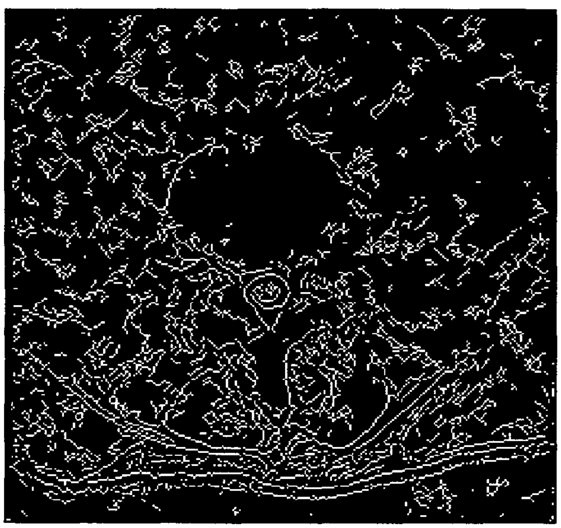

Figure 3b) Result of Canny edge detection

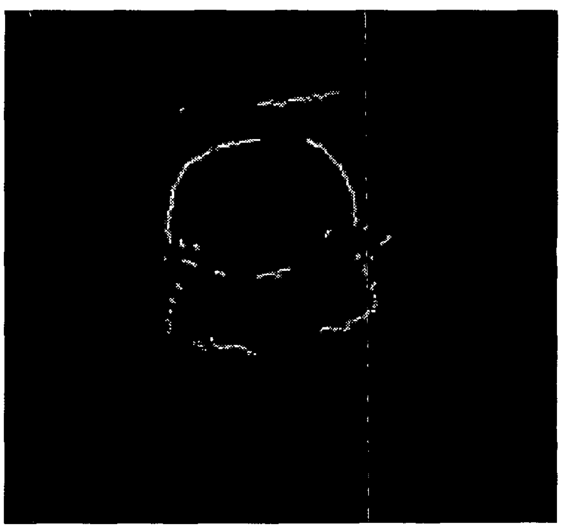

Figure 3c) Result of proposed radial edge detection

As discussed above, MR images provide very poor contrast between bone and soft tissue. Consequently, conventional edge detection techniques were not adequate to identify the weak edge that bounds the vertebral body in any cross-sections. Figure 3b show the poor results of a canny edge detector on a typical spinal cross-sectional image (Figure 3a) from the data set.

Some information about the nature of the edge is known that can be useful in designing a more effective edge detection scheme. Specifically, the direction of the edge is known, in that the edge is approximately perpendicular to a radial line drawn out from the centre of the vertebral body.

A radial edge detection scheme was developed for the vertebral body boundary. An approximate centre point of the vertebral body is estimated from the identified centre of the spinal cord (section 1). The following modified gradient operator is then applied radially from the centre point [2]:

$$\begin{bmatrix} -1 & -1 & -1 & 0 & 1 & 1 & 1 \\ -1 & -1 & -1 & 0 & 1 & 1 & 1 \\ -1 & -1 & -1 & 0 & 1 & 1 & 1 \\ -1 & -1 & -1 & 0 & 1 & 1 & 1 \\ -1 & -1 & -1 & 0 & 1 & 1 & 1 \end{bmatrix}$$

This operator also has a significant smoothing component to reduce the effects of random noise. The operator is applied radially in all directions with an increment of one degree. The pixel that yields maximum response to this mask in each direction is considered an edge point. Also, since the location of the edge does not change significantly between adjacent cross-sections, further noise robustness can be gained by adding the response to the mask in adjacent slices. The result is a multi-layer 3-D edge operator.

The results of this edge detector show a marked improvement over the results of the canny edge detection. Some erroneous edge points are caused by noise in the image, or by anatomical structures other than the vertebral body. Such edge points caused by noise or other small image structures can be eliminated easily by eliminating clusters of adjacent edge points below a threshold size of ten pixels. Longer erroneous edges caused by larger image structures are more difficult to remove, but can often be eliminated based on distance from the estimated centre of the vertebral body. Figure 3c shows a typical result of the vertebral body edge detection on one cross-sectional image.

5. CONCLUSIONS AND FUTURE WORK

Various image processing techniques have been adapted heuristically to optimize low-contrast segmentation based on *a priori* knowledge of spinal MRI. Methods of characterizing vertebrae on the basis of location, rotation and scale have been developed. An active contour method has been successfully developed for segmentation of the spinal cord. Finally, a radial edge detection algorithm has been developed for detection of the boundary edge of the vertebral body in cross-sectional images.

Further work on this project will first entail the acquisition or development of a 3-D spinal model. Once an adequate model has been realized, research will progress into the application of deformable model to guide edge detection of the spinal processes.

6. ACKNOWLEDGEMENTS

P. Tate and M.Chapman are thanked for producing the MRI and CT imagery used in this study. GEOIDE (an NSERC Centre of Excellence) is providing the funding to support this research.

7. REFERENCES

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