Surface reconstruction of defect contours for medical image registration purpose

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ABSTRACT

Although, most of the abnormal structures of human brain do not alter the shape of outer envelope of brain (surface), some abnormalities can deform the surface extensively. However, this may be a major problem in a surface-based registration technique, since two nearly identical surfaces are required for surface fitting process. A type of verification known as the circularity check for the shape of the detected head contours was defined based on the curvature measurement. Any unacceptable deformity (or hole) existing in the brain surface can be detected by the circularity check and 'reformed' by a type of interpolation process. Two techniques were suggested to 'reform' the abnormal regions and holes on the surfaces: one based on median filtering and another based on contour reflection.

Keywords

Medical image analysis, Surface fitting, Contour detection, Curvature

Introduction

Both Medical imaging and surgical treatment, may require anatomical and physiological information as obtained by various modalities (e.g. CT, MRI, SPECT or PET) to be correlated with each other. Moreover, the knowledge of lesion activity as well as the determination of accurate boundaries is an essential factor in volume measurement, internal dose calculation and radiotherapy planning. The concepts of image registration and data matching have been considered by a number of researchers using different methods (3,6). If image registration is to be usable in clinical assessments then it should be simple, relatively inexpensive, and do not include any extra constraint for patient during the imaging process. If it is also to prove valuable judgments in clinical decisions, it must be accurate, free from subjective interaction error, and reliable in both normal and abnormal cases.

In recent years, effort has been concentrated on improving techniques which use the routine images taken without any special patient positioning or tedious setting of e.g. external markers on a patient. These techniques which are based on external surfaces of an object are also independent of noise and gray-level changes inside the object. However, the actual problems associated with an accurate and automatic registration of medical images remain unrevealed. So far, there is no reliable method to handle low resolution and noisy images from SPECT data set or where a defect presents in surface data due to an abnormal region.

The main task and major application of the surface reconstruction technique is found in recovering the 3-D external envelope of objects used in registration process (called surface fitting). Some reconstruction techniques involve 3-D boundary following whereas in some others only slice-level boundary detection is required. The later needs to be complemented by a surface formation process between the contours of successive slices. The major difference between various surface reconstruction methods lies in the method of interpolation applied between the contours of successive slices.

Surface reconstruction consists of several stages. In general, these can be defined as segmentation, contour detection, and surface formation. Surface formation needs to be applied after a series of 2-D contours are initially detected from the original cross sectional images (3). A problem exists where some tumors or abnormal structures deform the contour of an object (e.g. Brain). In this paper, the problem of the correspondence between the registering points of two surfaces in the deformed region and some techniques to resolve these problems are addressed.

Materials and Methods

The boundary detection algorithm used in the current application was a sequential type process based on three criteria, edge direction map, gradient magnitude, and connectivity (1-2,4-5). Both, Grey level thresholding and gradient based methods were used to detect edges of an object. The process was designed to switch between these two methods based on the characteristics of the image. In general, these algorithms were used to track boundary of object and to check its desirability.

The edge direction map is also used to examine the local connectivity of the edge points. If the direction at the center of a 3*3 (compass gradient mask) is k, then the edges are connected provided the directions of the proceeding and succeeding edge vectors are k-1, k or k+1. This means that the direction of a boundary segment is not more than 45 degrees from the direction of the previous or next boundary segment. The connected neighbors of pixel **P**(i,j) are defined as:

$N_{P(i,j)}=\{\mathbf{P}(\ell,m)\ 0<\mathrm{Max}(|i-\ell|,|j-m|)\leq 1\}$

Where ℓ and m correspond to x and y coordinates of any neighbor of the current pixel.

Curvature information was then used as a shape based criterion to examine the detected boundaries based on a priori knowledge of the object boundary. Slope and curvature are important contour segmentation criteria. These two are the most useful geometrical properties describing the shape of an object and the relational information among subsets of a single digital object (e.g.; curves or segments of them). The slope at a point was derived from its tangent vector, whereas curvature was defined as the rate of change of this slope. Both, slope and curvature at a point **P** were defined as the slope and curvature of a line segment on each side of **P** along the curve. Using a line segment enabled smoothing of the slope/curvature and thus the noise suppression on a contour was also achieved. The length of the line segment determines the amount of smoothing and should not be bigger than a straight line required fitting the curve segment starting at **P.**

Significant features on a curve are defined as the points where the absolute curvature is high (the slope changes abruptly)(7,8), or where the sign of the curvature changes. These are defined as corners (angles) and inflections, respectively. The inflections give useful information about convexity and concavity of a curve, and are also important features of a contour image.

Two methods were implemented for calculation of the curvature. For a one-dimensional curve $y=f(x)$, curvature is expressed as a function of arc length and in terms of the derivatives at a point x.

$$\mathbf{K}(x) = f''(x)/(1+(f'(x))^2)^{3/2}$$
$$= (d^2y/dx^2)/(1+(dy/dx)^2)^{3/2}.$$

Where $f'(x)$ and $f''(x)$ are the first and second derivative of the function $f(x)$. The curvature can be defined on a digital curve ($\mathbf{P}_i=(x_i,y_i)$, $i=1,...,n$) by replacing the above derivatives by differences. In this respect, a smoothed slope is considered to be $(y_{i+k}-y_i)/(x_{i+k}-x_i)$ for some integer $k\geq 1$.

The curvature can also be defined as the cosine of the angle between two k-vectors a_{ik} and b_{ik}, where;

$$a_{ik} = (x_i-x_{i-k}, y_i-y_{i+k})$$
$$b_{ik} = (x_i-x_{i-k}, y_i-y_{i-k}),$$

and the choice of k acts as a smoothing factor. The cosine of the angle between each two curve segments can then be expressed as

$$C_{ik} = (a_{ik}.b_{ik})/|a_{ik}||b_{ik}|,$$
$$C_{ik} = (\Delta x^+)(\Delta x^-)+(\Delta y^+)(\Delta y^-) / (\sqrt{((\Delta x^+)^2+(\Delta y^+)^2)}\sqrt{((\Delta x^-)^2+(\Delta y^-)^2)}),$$

Where $\Delta x^+=x_i-x_{i+k}$, $\Delta x^-=x_i-x_{i-k}$, $\Delta y^+=y_i-y_{i+k}$, and $\Delta y^-=y_i-y_{i-k}$.

Having found the curvature at every point $\mathbf{P}_i(i=1,...,n)$ of a detected boundary image, their values are compared with a pre-set threshold value to check the desirability of the angles and curvatures of the boundary points. Since this curvature threshold value corresponds to a well-defined regular and approximately circular shape of the head contour, this process is referred to as circularity check.

The technique used to reconstruct (reform) a hole or deformed region depends on the size of lesion. The application of the median filtering on original 2-D grey-scale slices reformed some of the holes and deformities (fig. 1). The maximum usable size of the filter was restricted by the size of the normal regions which occupy half of the filter size, when this filter was placed on the hole region. However, the use of this filter was limited only to a deformed region whose size was relatively small compared to the size of the normal region occupied inside the filter.

An alternative technique for the surface reformation was used by reflection of normal part of contour, from one side, on abnormal part of the other side (fig. 2). Therefore, this technique uses the symmetry of the right side of

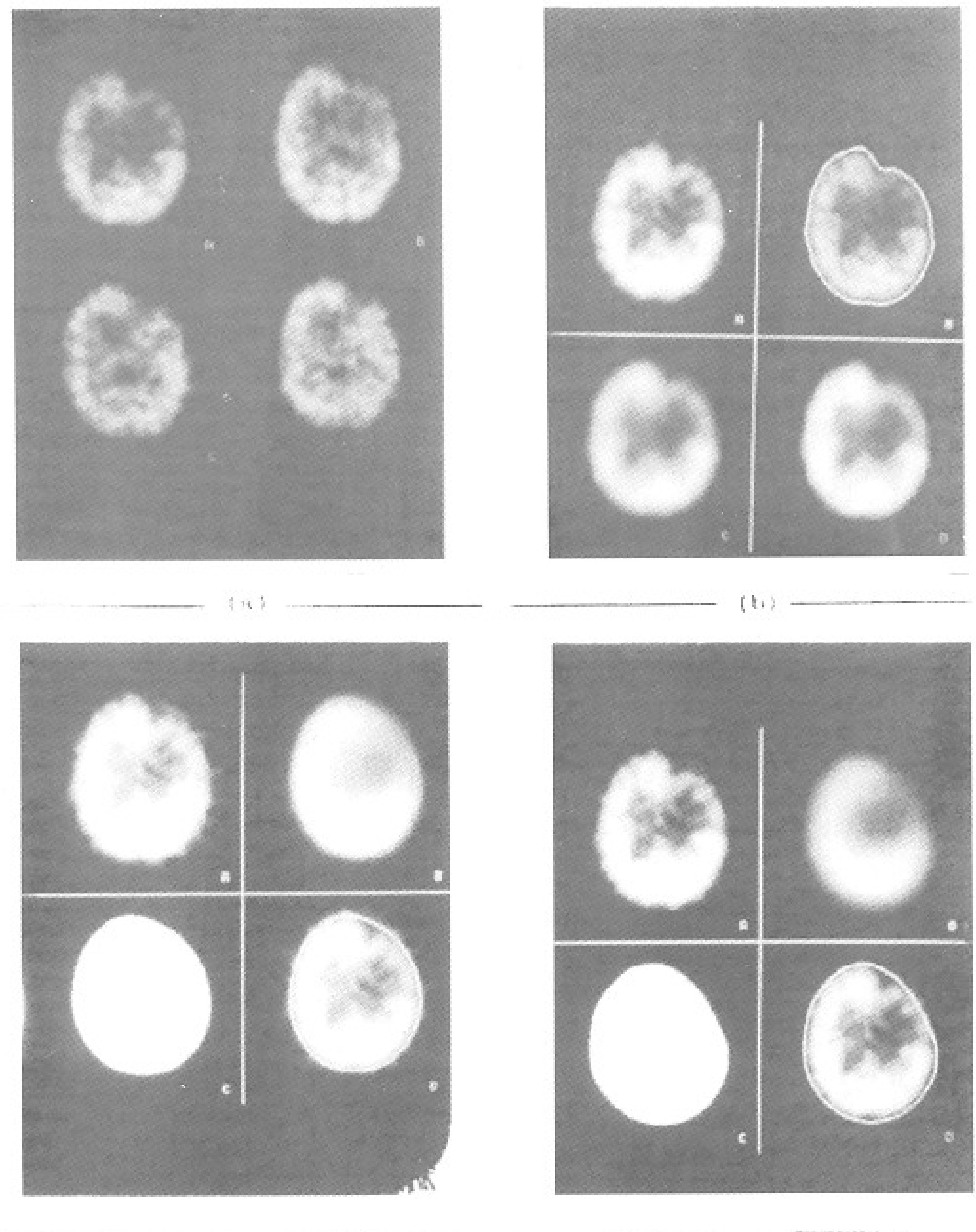

Figure 1

Figure 1- Contour detection of SPECT images showing a defect region in frontal lobe. a) Original Slices. b) Contour extracted after smoothing using a low pass filter. c-d) Contours after applying a big size Median filter.

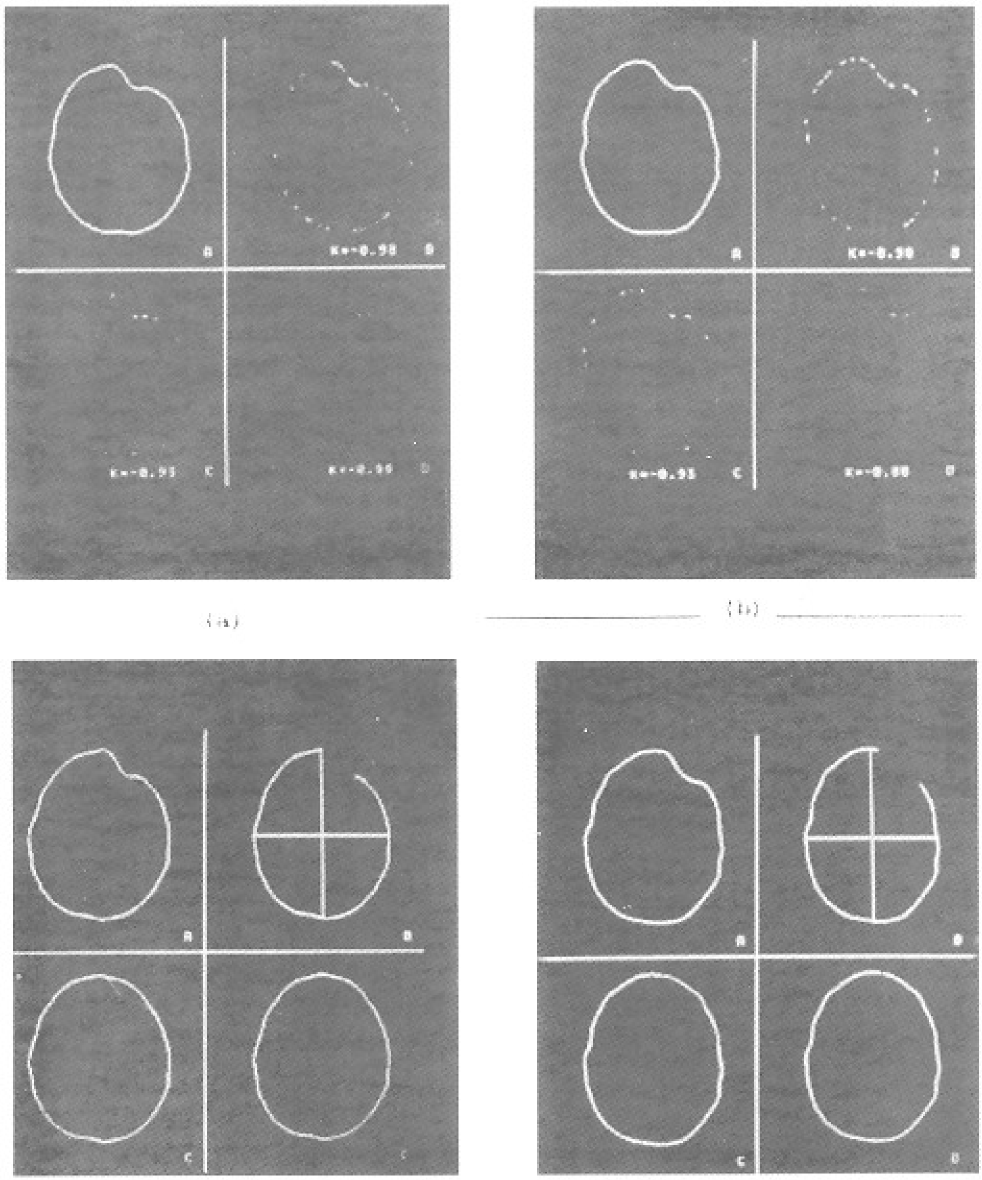

Figure 2- Contours extracted from abnormal SPECT images. a-b) High curvature points obtained at different threshold (sub-image b-d); c-d) the surface reformation was used by reflection of the normal part of contour

the head to its left side. Two principal axes were used as a base line on the contour image, one dividing the 2-D head image into equals left and right sections, and one splitting it into anterior and posterior regions. Then, all reflections were performed with respect to these principal axes.

Results and Discussion

The object of interest (the external surface of the head or brain) should have a smooth surface with connected boundaries, a regular shape, and an approximately circular outline. Exceptions are likely in some abnormal clinical situations where a lesion deforms the external surface. Figure 1 shows a typical SPECT image of a brain from a HMPAO radiotracer study with a severe abnormality. The irregularity of the brain edges is not unexpected in a normal brain structure. Presence of low intensity region (e.g. cold region or hole) is due to an abnormal brain tissue (tumor). However, normal or even abnormal structure of a brain may not alter the smoothness and circularity of the outer envelope of the brain image. In general, in order to create two nearly identical surfaces for the registration process, a smooth and complete surface must be reconstructed from the SPECT data. The result of applying a median filter of size 51*51 is demonstrated in figure 1(c-d). As shown in this image, the defected contour can be reconstructed approximately by an acceptable degree.

First, a circularity check was performed on the contours to detect any deformities, such as holes (cold regions) on the surface. The angular measurements from adjacent line segments provide an approximation of the change of the slope along the boundary. Comparing the rate of change of the slope with a constant threshold value (i.e.; expected curvature defined as a

Predefined threshold) indicates any possible undesirable deformity as well as the start and end points of this lesion.

The original contours detected by the contour tracking algorithm, and the points having undesirable curvatures are shown in figures 2a and 2b. During the circularity check, all points with undesirably high curvature are displayed to the operator. The operator can then manually alter and eliminate the unwanted points. The desirability of a curvature value in a deformed region is then automatically decided by setting a curvature threshold value. Visual inspection of displayed contours also plays an essential role in confirming or rejecting the automatic decision.

The result of applying reflection technique is shown in figure 2(c-d). As shown in this figure, the principal axes are determined based on the normal structures of the image. The symmetry of the trans-axial head cross section is an important factor for estimating the principal axes of an abnormal head image slice. The principal axes on defected contours (major and minor axes) can be obtained by examining the direction of the principal axes in a normal image slice above or/and below the deformed slice. The centroid is then computed as the central point, on the principal axes. This process is performed automatically, but may be interactively controlled under visual assessment.

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