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Detection of Colon Wall Outer Boundary and Segmentation of the Colon Wall Based on Level Set Methods

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Abstract— **Virtual colonoscopy (VC) has become a more prevalent and accepted method to diagnosis colorectal cancer. An essential element to detecting cancerous polyps using VC in conjunction with computer-aided detection is the accurate segmentation of the colon wall. While the inner boundary of the colon wall, the lumen-mucosal boundary, has often been the focus of previous colon segmentation work, detection of the outer wall, the serosal tissue boundary, allows for the segmentation of the colon wall, which is useful in determining both potential polyps, muscular hypertrophy and diverticulitis of the colon. Unfortunately, automatic determination of the outer colon wall position often is difficult due to the low contrast between CT attenuation values of the colon wall and the surrounding fat tissue. We have developed a level set based method to determine from a CT colonography (CTC) scan the location of the colon serosal tissue boundary. After determining this location, the algorithm segments the entire colon wall at subvoxel accurate precision. The algorithm has been validated on several CTC datasets.**

I. Introduction

Colorectal cancer is the second leading cause of cancer related deaths among men and women in the United States [1]. Fortunately if precursor polyps are detected early in their course and successfully resected, most colon cancers can be prevented. CT colonography (CTC) is an emerging technique for non-invasively performing colon cancer screenings [2]. During this procedure, a patient has his/her colon insufflated and undergoes an abdominal CT scan from which a 3D virtual model of the colon can be constructed. This model then can be inspected in a virtual colonoscopy (VC), a computer procedure simulating conventional optical colonoscopy. A VC model also can be analyzed automatically to assist a radiologist in the detection of polyps [3].

Computer-aided detection (CAD) of polyps in VC requires detecting areas of the colon wall surface that have properties characteristic of polyps. One such property is colon wall thickness. Determination of the thickness of the colon wall is also important for diagnosis of other colonic diseases, such as muscular hypertropy and diverticulitis. Manual determination of the colon wall thickness can be very time consuming. In addition, it is often difficult to determine the precise location of the boundaries of the colon on 2D slices due to partial voluming effects.

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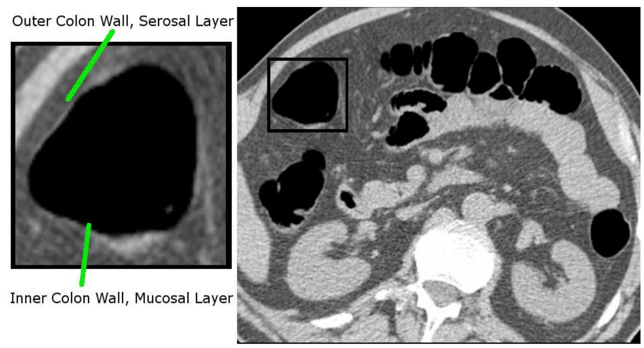

Figure 1: Slice of CTC scan showing colon wall. Notice the low contrast between the colon outer wall and the surrounding tissue.

Segmentation of the colon lumen is often performed as part of creating a 3D model for VC or as an initial step in CAD of polyps. The large difference in CT attenuation values between the lumen and inner, mucosal layer of the colon wall is easily distinguished by traditional segmentation techniques, such as threshold region growing. However, the contrast between the colon wall's outer serosal layer and the fat surrounding the colon is not as large of a difference and is often more difficult to distinguish visually, Figure 1. This low contrast boundary can often cause difficulties in segmenting the outer colon wall from the surrounding tissues.

This paper describes a novel algorithm for determining the outer wall of the colon and segmenting the entire colon wall. The algorithm automatically and accurately calculates the colon wall segmentation with subvoxel accurate precision. The segmentation has been verified on several CTC datasets.

II. Background

A. Level Set Methods

Recently, level set based approaches have been used to segment objects, many of which have been applied to colons. Level set methods evolve an isosurface in the direction of the surface normal [10]. In its general form the evolution speed can depend on position, normal direction, curvature, and shape, and the isosurface can cross over the same point multiple times. The general form of the level set method equation is as follows:

$$\frac{d}{dt}\psi = -\alpha\vec{A}(x)\cdot\nabla\psi - \beta P(x)\,|\nabla\psi| + \gamma Z(x)\kappa\,|\nabla\psi|$$

where ψ is the level set function, A is an advection term, P is a propagation term, Z is a spatial modifier term for the mean curvature term κ, and $\alpha, \beta, \text{and}\, \gamma$ are weights which determine the influence of each of these terms on the movement of the isosurface. Level set methods can be used to segment objects in the presence of noise and incomplete information, with the result defining the object boundary at subvoxel accuracy [4]. The method results in an image which contains positive level set values within the object and negative level set values external to the object from which the colon boundaries can be interpolated.

We apply the general level set method during the segmentation of both the inner and outer colon walls from the CT virtual colonoscopy scans. Due to the contrast difference between the colon wall and lumen, a threshold level set segmentation method, which is based only on a lower and upper threshold value for the propagation term, is used for a subvoxel accurate lumen segmentation. A more complex geodesic active contour level set method [5], which has an advection term that attracts the level set to the object's boundary, is used as part of the algorithm to determine the outer wall boundary.

B. *Colon Wall Segmentation*

Typically the colon wall is inspected after performing a segmentation of the inner, mucosal wall, and creating a colon surface. The lumen segmentation is often performed using a simple threshold region growing method [6]; the large difference in CT attenuation values between air and colon wall tissue allow the use of threshold methods to distinguish between the two regions during the segmentation. More sophisticated methods have also been used to segment the lumen by combining threshold region growing with level set methods to result in a smooth subvoxel accurate segmentation [7].

Unfortunately, very few prior methods have tried to detect the outer colon wall, which is the boundary between the serosal layer of the colon wall and the fat tissue, due to the low contrast, i.e. similar CT attenuation values, between the colon wall and surrounding tissue. Wang, et al. [8] presented a method of polyp detection which incorporated the detection of the outer colon wall boundary. They create a stepwise-like profile of the CT data along three orthogonal rays emitted from a point on the lumen-colon wall boundary and assume that the ray will intersect with the outer colon wall boundary. The first- and second-derivatives of the profile are inspected for a specific variance pattern to determine where the boundary of the colon outer wall is present. The resulting boundary only exists at the point of intersection along the three rays which are profiled and often the boundary that is detected is located at the inner lumen-colon wall boundary due to partial voluming effects, rather than at the actual outer wall boundary.

Level set based methods have also previously been used to determine the boundary between low contrast tissues. The algorithm presented by Zeng, et al. [9], maximizes the probability of a boundary occurring between tissues by assuming a Gaussian distribution of values in each of the tissues. Although this method works very nicely for certain tissues, such as the white matter in the brain, which has intensities between the neighboring gray matter and cerebrospinal fluid intensity values, the method breaks down for colon wall tissue, which has intensities higher than both neighboring tissues, air and fat tissue. The partial voluming effect makes partial air voxels indistinguishable from fat voxels.

The algorithm presented in this paper expands on both the profile method of Wang, et al. [8] and the level set methods of Zeng, et al. [9] to develop an algorithm for accurately determining the entire outer boundary of the colon wall at subvoxel precision.

III. METHODS

A. *Lumen Segmentation*

The accurate segmentation of the colon lumen is necessary as the initial step of the outer wall segmentation. As stated above, the lumen may be segmented by a simple threshold region growing segmentation. We chose to use the value of -500 HU as the segmentation threshold for the lumen-colon inner wall boundary because it is the value which is half-way between the air, -1000 HU, and soft tissue, ~0 HU. This segmentation results in a coarse lumen segmentation, and the lumen segmentation is made more accurate through a threshold level set method. The threshold level set method uses the threshold region growing segmentation as the initial level set boundary and the value of -500 HU to determine a subvoxel accurate segmentation of the colon lumen, Figure 2.

B. *Speed Function*

The creation of an accurate speed function for the level set algorithm is necessary to ensure a precise segmentation. The level set segmentation methods use the speed image to determine where the level set surface should evolve and where it should halt.

The speed image used in the outer wall level set segmentation is calculated from both the lumen level set image and the original CT image. A 3D directional derivative of the CT image is performed in the direction perpendicular to the level sets produced by the lumen segmentation, Figures 3 and 4. The local non-maximum gradients along the level set expansion direction are suppressed to further avoid the impact from noise and partial voluming effects from the lumen-colon wall boundary. A sigmoid filter is used on the directional derivative image emphasizing the particular set of values where the directional

Figure 2: Results of lumen segmentation on a slice of a CTC scan.

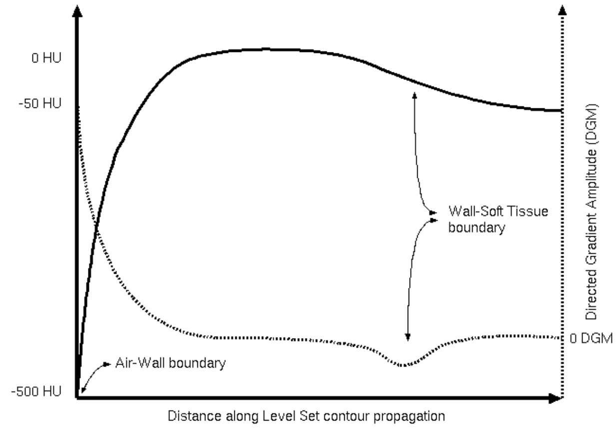

Figure 4: Intensity profile of CT (solid line) and gradient magnitude (dotted line) values along directed ray from colon lumen to outer wall.

derivative is high, i.e. where the outer colon wall boundary is located. Inverting the output of the sigmoid filter allows a speed image to be created such that the level sets will propagate where there is a low directional gradient in the original CT image and stop when a high gradient along the colon outer wall is encountered.

C. Colon Outer Wall Segmentation

The level set segmentation of the colon outer wall is computed by using a 3D geodesic active contour level set segmentation method. The lumen level set segmentation is used as the initial level set boundary and the speed image is calculated from the directional derivative of the original CT image, as described above. The geodesic active contour level set segmentation method uses the advection term which attracts the level set evolution to the high gradient values in the feature image and a curvature term that prevents the evolution of the boundary from exceeding a maximum curvature. This level set method adheres to all near zero values in the speed image and fills in the missing regions in an intuitive way, producing an outer wall segmentation that combines the confident location of boundaries seamlessly with expected boundaries. The zero isocontour in the resulting level set image represents the outer colon wall.

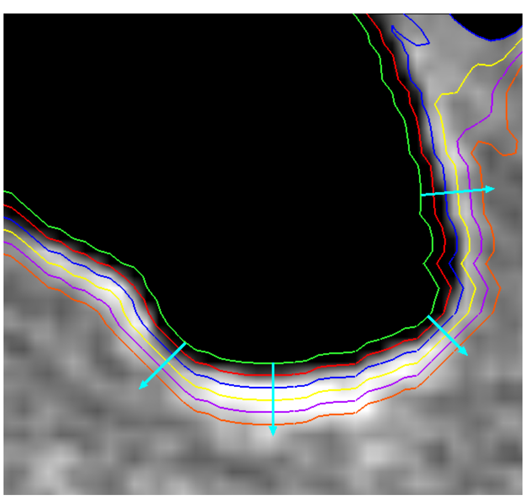

Figure 3: Derivative of CT image calculated in direction, represented by vectors, perpendicular to the lumen level sets.

IV. Results

The algorithm presented was performed on 3 CT virtual colonoscopy scans each containing 512 x 512 x 512 images with a spacing of 0.7 x 0.7 x 1.0 mm^3. The colon wall in these scans consisted of various thicknesses throughout each colon segment. The results of performing the segmentation algorithm on these cases can be seen in Figures 5 - 7.

V. Discussion

Figures 5 and 6 show the subvoxel accurate segmentation of the colon wall. The accuracy of the segmentations was

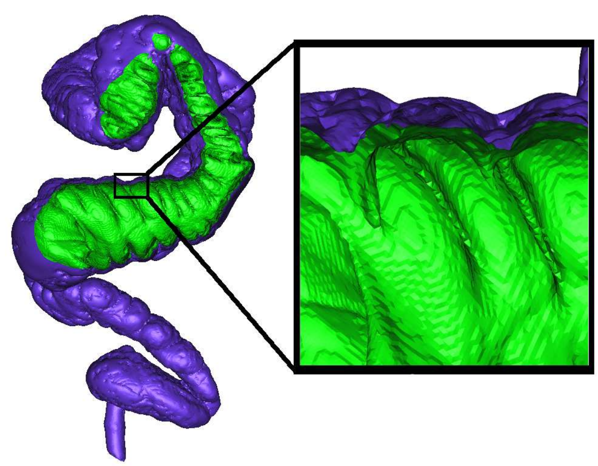

Figure 5: Colon with cutting-plane showing segmentation of lumen (green) and outer colon wall (purple).

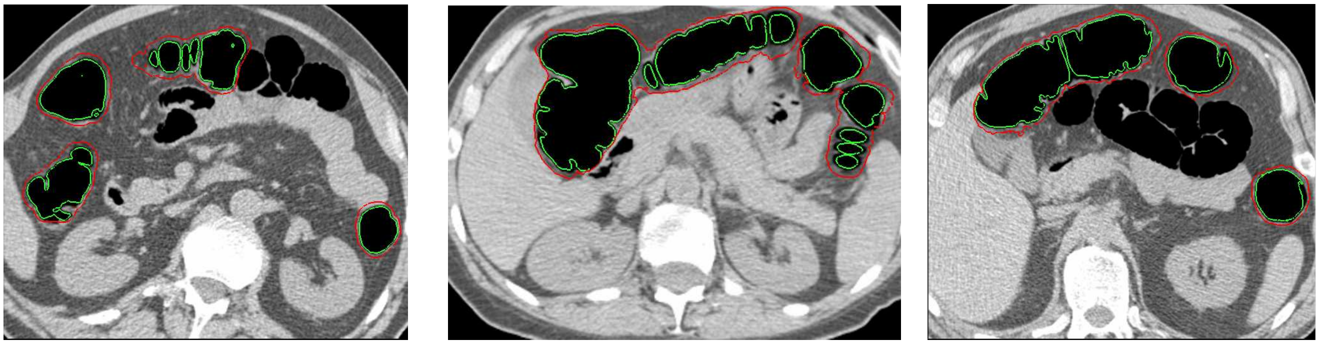

Figure 6: Colon wall segmentation for 3 different CTC scans: colon inner boundary shown in green, colon outer boundary shown in red.

verified visually. The outer boundary of the colon wall has been determined, even though there is low contrast between the colon wall and the surrounding fat tissue. The method is also fully automatic, thus requiring no user intervention. Even in areas where the colon is adjacent to other organs, the algorithm accurately finds the colon outer wall, as shown in Figure 7.

Using the derivative of the CT values along the direction perpendicular to the level set surfaces of the lumen segmentation has allowed for an accurate detection of the colon outer wall. Further, the use of the geodesic level set method has allowed for a smooth subvoxel accurate colon wall segmentation to be performed. When determining the position of the colon outer wall by starting at the lumen segmentation and considering the gradient direction relative to the lumen level set gradients, we avoid the partial voluming effects between the colon lumen and wall, which cause difficulty in accurately segmenting the colon wall using prior algorithms. Also in contrast to prior algorithms, the presented algorithm will not result in finding the outer boundary within the lumen because our algorithm is initialized with the lumen segmentation. Finally, the resulting segmentation contains an entire surface, while prior techniques may only find several points on the outer colon boundary.

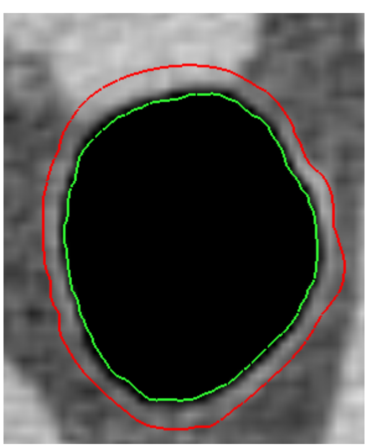

Figure 7: Zoomed in area of colon wall segmentation adjacent to small bowel in upper portion of picture: colon inner boundary shown in green, colon outer boundary shown in red.

VI. Conclusion

This paper has presented an automatic algorithm for determining a subvoxel accurate segmentation of the colon wall. The method can result in appropriate segmentations when the colon wall is thick or thin. The resulting accurate segmentations of the colon wall may be useful in detecting spasms, cancers, and potential polyps for virtual colonography computer-aided detection, and automatically determining the colon wall thickness for diagnosis of muscular hypertropy and diverticulitis.

Acknowledgments

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