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# Improved diagnosis and navigation for CT colonography

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# Improved Diagnosis and Navigation for CT Colonography

by

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# Abstract

This project describes the development of an automatic segmentation method and a novel navigation system that detect polyps using advanced image processing and computer graphics techniques. The colon wall segmentation method from the CT data set of abdomen is achieved by combining the active contouring model – level set method and the minima detection using mathematical morphology theory. Polyp detection is attained by analyzing surface curvature and texture information along on the colon wall. Adding texture analysis provides a new feature for improving currently existing methods. As such, polyp candidates are examined not only by their shape and size but also by their texture appearance.

# Acknowledgements

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# 1. Introduction

## 1.1 Clinical Problem

Colorectal carcinoma currently ranks as the third most common human malignancy and the second leading cause of cancer-related death in North America [1]. Unfortunately, colon cancer is most often discovered after the patient develops symptoms, and by then, the likelihood of a cure has diminished substantially. Earlier detection and removal of polyps is the key to prevent colon cancer and can eliminate colon cancer in 90% of patients [2].

## 1.2 CT Colonography

Conventional colonoscopy is the most accurate diagnostic procedure for detecting polyps that is currently available. However, it is expensive, invasive, uncomfortable, time consuming and carries a small risk of perforation and death. Patients are often reluctant to undergo earlier examination [4].

However, conventional colonoscopy is not feasible as a population screening test since endoscopists are not of sufficient number to accommodate the entire populations of patients. A minimally invasive, safe, and low-cost method to

evaluate the colon for pre-malignant polyps and early, curable colon cancer would be preferred by most patients.

Recently, Computed Tomography Colonography (CT Colonography) has been developed as an alternative method to evaluate the entire colon for polyps [5] which leads to an easier, more comfortable examination than other screening tests.

CT Colonography is a diagnose procedure of colon cancer that uses CT images of patient's abdomen. Radiologists examine the colon through the CT data set and the surfaces of colon are constructed using advanced computer graphic technologies to detect polyps from CT images. The first CT colonoscopy system reported in the medical imaging literature was in the year 2000.

CT Colonography provides a safe, minimal-invasive approach to detect colonic polyps using medical imaging and computer graphics technologies with 3D software to create virtual endoscopic images of the colonic surface. CT Colonography has been advocated as a technique for providing mass screening for colorectal carcinoma. It has emerged as a promising alternative procedure, with potentially lower complication rate, improved patient comfort and patient acceptance.

Currently, however, CT Colonography is still impractical, mostly due to the following restrictions:

1. There are limitations in the accuracy and robustness of current computer aided detection (CAD) techniques for polyp detection, thereby reducing the efficiency of radiologists in detecting polyps. There has been considerable variation in the reported accuracy of CT Colonography. Several studies have reported sensitivities of greater than 90% for detection of lesions sized 10 mm or more, [6-9] but other studies reported lower data ranging from 61% to 78%. [10-13] The largest recent single-center study reported poor results and considerable variation between readers, with sensitivities of 32%, 34%, and 72%. ([14] Most recently, Cotton et al. have reported that the sensitivity of CT Colonography for finding participants with 1 or more lesions sized at least 6 mm was 39.0% and for lesions sized at least 10 mm it was 55.0%. These results were significantly lower than those for conventional colonoscopy, with sensitivities of 99.0% and 100%, respectively [15].

2. Current CT Colonography techniques are time consuming. A typical CT Colonography examination produces 150-350 axial CT images each for the supine and prone imaging data sets, yielding a total of 300-700 images/patient. Despite the recent advances in image display technologies, studies show that the case interpretation time is still between 15 – 40 min even when reading is done by experts in abdominal imaging, [16][17].

3. The interpretation time for an entire CT Colonography examination should be reduced substantially before CT Colonography can be successfully translated from the research arena to routine clinical practice.

## 1.3 Cancer Relevance

Accordingly, it has been suggested that CT Colonography can not be used as the sole diagnostic tool in the detection of early colorectal carcinoma until the low accuracy of polyp detection and procedure time are improved.

This research project aims to improve upon the current methods of CT Colonography in accuracy, speed and early polyp detection, which are the most common precursor of colorectal carcinoma. A computer assisted diagnosis (CAD) system that improves the current system has been investigated and developed with special emphasis on increasing the accuracy of polyp detection that leads to more chances of cancer cure. In addition, our system reduces X-ray radiation and provides a computed cleansing procedure that may eliminate the need for physical bowel preparation. Supine positioned CT scans of patient abdomen is used in our approach that improves the current method using both supine and prone positioned CT scans. Therefore the X-ray radiation exposure to patients reduced by 50%.

As in Conventional Colonoscopy, it is essential that during CT Colonography all colonic mucosal surfaces must be adequately visualized and examined. This includes potential "blind spots" situated behind prominent mucosal folds, especially within redundant, tortuous segments of colon. The colonic wall must be viewed circumferentially.

A unique viewing system is under development in this research. This new system provides a way for more complete examination of the colonic wall, including the "blind areas".

Through the collaborative efforts of clinical radiologists and computer graphic scientists, the individual techniques that are under development are integrated into a cohesive and complete methodology that specifically addresses and provides solutions to the current limitations of CT Colonography as documented in the medical literature and achieves a faster, patient-friendly procedure, with improved accuracy, and internal quality assurance.

The techniques developed in this research will achieve these improvements by accomplishing the following goals:

### 1.3.1 Active Contour Modeling and Gray Scale Analysis

The post-processing technique will employ minima detection, Active Contour Modeling techniques to perform colon segmentation, which will improve the

robustness of the segmentation method for abstracting colon from the raw CT data.

After the colon has been segmented, the gray scale information will be analyzed to enhance the detection of polyps. This will improve upon the accuracy achieved by previous methods that rely solely upon surface shape information. We will analyze very detailed gray scale information as well as the colon surface curvature information.

### 1.3.2 Reduction of Radiation Exposure

The CT Colonography procedure will be performed with the patient in a supine position only (as opposed both supine and prone positioning that is commonly used at the present). This approach will reduce radiation exposure to each patient by 50%.

### 1.3.3 Navigation System

This new system, which is constructed from 3 combined components, provides for more complete examination of the colonic wall, including the "blind areas" that are obscured during the colonic fly-through portion (in another word, screening portion) of the CT Colongraphy exam.

# 2. Background

Studies on the diagnostic accuracy of CT Colonography currently remains inconclusive, with several studies citing perceptual errors and observer experience limiting overall accuracy. Although clinically significant colonic polyps are resolvable, given the spatial resolution of helical, multi-detector computed tomography (CT), the accuracy and efficiency of viewing hundreds of axial images per exam are limited by human factors, such as attention span and eye fatigue.

In response to this challenge, a variety of computer-aided diagnosis (CAD) methods have been developed to improve both the accuracy and the efficiency of lesion detection in CT Colonography, as well as other diagnostic imaging examinations which require solutions to difficulties in three dimensional imaging.

Several different techniques and approaches to CAD for CT polyp detection have been developed:

Vining et al [18] developed a method that measures abnormal wall thicknesses using heuristics. Other approaches have analyzed the morphology of the mucosal surface. Summer et al [19, 20] have developed a method that uses size, attenuation, and curvatures calculated with convolution-based partial

derivatives to find polyps. A software application [21, 22] is used with "filter 7" function to detect polyps. A reduction of the number of false-positive was achievable by sampling the CT numbers of each voxel within a possible polyps along a ray directed through the polyp.

Yoshida et al [16, 17] used shape index and curvedness (computed with partial derivatives), directional gradient concentration, and quadratic discriminant analysis using both prone and supine datasets. Kiss et al [23] combined surface normal and sphere fitting methods. In addition, secondary CAD algorithms that are designed to reduce the false-positive rate of primary CAD algorithms have been proposed. Gokturk et al [24] applied support vector machines to shape and attenuation features to reduce false-positive's and reported a 50% increase in specificity at a sensitivity level. Acar et al [25] have applied edge displacement fields to reduce false-positives and reported a 23% increase in specificity at a constant sensitivity level.

Paik et al [26] employed surface normal overlap method which uses a statistic model of anatomic shapes to simulate CT data to achieve polyp detection. This methodology is able to distinguish between polyps and background anatomy such as haustral folds.

These previously described CAD algorithms have achieved varying levels of accuracy although they all leave room for improvement.

## 2.1 Patient-Oriented Issues

Despite initial enthusiasm for CT Colonography, a wide range of accuracy of the technique has been reported in clinical trials. While Cotton et al suggest that the experience and training of the Radiologist reading the CT Colonography may be a significant factor, but it is not yet proven [27]. There are, however, a variety of patient-related and technical limitations that can reduce accuracy, including poor bowel preparation as well as anatomically-related problems, such as flat colonic lesions, mobility of the colon, and blind-areas behind mucosal folds.

Some publications reported on computed cleansing methods to assist colon segmentation. Chen et al. employed a principle component analysis on local intensity vector [28]. Artifacts are presented at locations where gas, colon wall, and contrast enhanced fluid are connected. Polyps of 5mm in diameter, if located at these junctions could potentially be missed.

Lakare et al [29] described a cleansing method using segmentation rays. Their method requires the user to carefully study and select intersection characteristics and assign classification and reconstruction tasks to the ray. The junctions of three materials are not modeled. In other words, most current segmentation methods can not handle a less strict colon preparation scheme.

Serlie et al [30] proposed a cleansing method using histogram information in the image data. Over-segmentation could occur when the image data set has poor contrast. An accurate, robust and efficient method would improve the system.

## 2.2 Viewing System for Blind Spots

As stated above, one of the key goals of this research project is to investigate a robust method for earlier and more accurate polyp detection. As in Conventional Colonoscopy, it is essential that during CT Colonography all colonic mucosal surfaces must be adequately visualized and examined. This includes potential "blind spots" situated behind prominent mucosal folds, especially within redundant, tortuous segments of colon. The colonic wall must be viewed circumferentially.

Several investigators have addressed the issue of "unviewed regions" in CT Colonography [31 - 34]. Most recently, Hiyashi et al described a technique to detect undisplayed regions during fly-through and to perform quantitative evaluation [35]. In this process, the undisplayed regions are detected by marking displayed triangles for surface rendering or displayed voxels for volume rendering. The voxels or triangles not having displayed marks are considered to be undisplayed triangles or voxels.

Despite the problems created by blind areas, Cotton et al reported that the incorporation of the fly-through data with the initial axial CT evaluation increased the sensitivity of CT Colonography for the primary outcome (detection of participants with lesions <6 mm) by 17% to 56% but reduced specificity by 5%. For participants with lesions sized at least 10 mm, the fly-through data increased the sensitivity by 12% to 67% and decreased the specificity by 1% [27]. Thus, any methodology that helps ensure that all mucosal surfaces are adequately visualized and examined, including the blind areas, potentially, could simultaneously improve detection rate, as well as to serve as an internal quality assurance measure of the technique itself.

We are developing a software solution to the problem of "blind areas" or "unviewed regions" in CT Colonography, incorporating three connected techniques and methodologies including Virtual Colonoscope Mucosal Coloration, and the Navigation System.

# 3. Methods

## 3.1 Colon Lumen Detection

A gray scale minima detection using mathematical morphology [39] was applied to detect the colon lumen from the CT images of abdomen. This approach generates markers on every colon piece within the image and produces initial curves of active contour model for colon wall segmentation.

Mathematical morphology is a broad set of image processing operations that process images based on shapes. Morphological operations apply a structuring element to an input image, creating an output image of the same size. In a morphological operation, the value of each pixel in the output image is generated based on a comparison of the corresponding pixel in the input image with its neighbors. By choosing the size and shape of the neighborhood, one can construct a morphological operation that is sensitive to specific shapes in the input image.

A structuring element is a matrix consisting of 0's and 1's that can have any arbitrary shape and size. Structuring elements are typically much smaller than the image being processed. The center pixel of the structuring element, called the origin, identifies the pixel of interest, or the pixel being processed. When a

morphological operation is carried out, the origin of the structuring element is typically translated to each pixel position in the image, and then the points within the translated structuring element are compared with the underlying image pixel values. The details of the comparison and the effect of the outcome depend on which morphological operator is being used. By combining dilation and erosion operators one can obtain algorithms for many image processing tasks, such as feature detection, image segmentation, image sharpening, and image filtering, etc.

### 3.1.1 Dilation

Dilation of a binary image A by a structuring element B is defined by,

$$A \oplus B = \{c \mid c = a + b \text{ for some } a \in A \text{ and } b \in B\}$$

For each background pixel the structuring element is superimposed on top of the input image so that the origin of the structuring element coincides with the input pixel position. If at least one pixel in the structuring element coincides with a foreground pixel in the image underneath, then the input pixel is set to the foreground value. If all the corresponding pixels in the image are background, however, the input pixel is left at the background value.

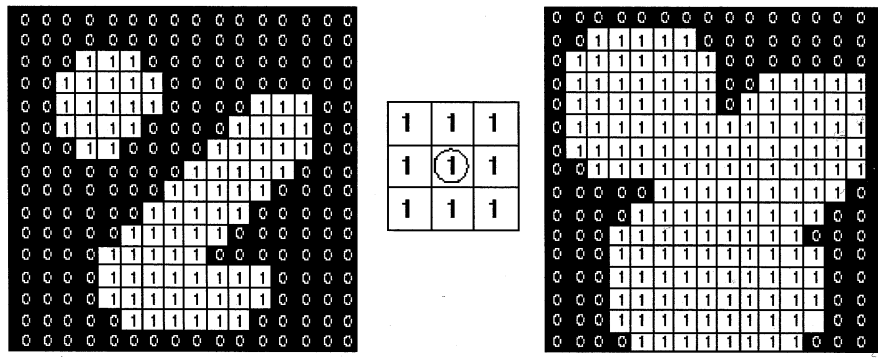

Figure 1: Dilation by a 3 x 3 structuring element

### 3.1.2 Erosion

Let A denote a binary input image and B denote a structuring element, then the erosion of A by B is given by,

$$A \ominus B = \{x \mid x + b \in A \text{ for every } b \in B\}$$

Erosion is similar to dilation in that if for every pixel in the structuring element, the corresponding pixel in the image underneath is a foreground pixel, then the input pixel is left as it is. If any of the corresponding pixels in the image are background, however, the input pixel is also set to background value.

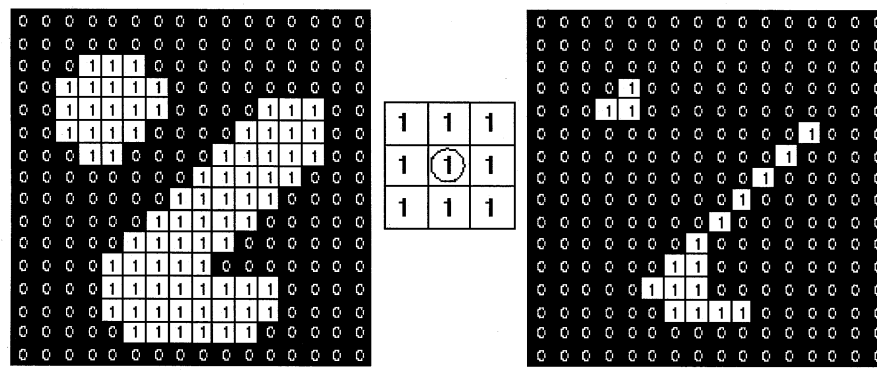

Figure 2: Erosion by a 3 x 3 structuring element

### 3.1.3 Opening

Opening of A by B is obtained by the erosion of A by B, followed by dilation of the resulting structure by B,

$$A \circ B = (A \ominus B) \oplus B$$

While erosion can be used to eliminate small clumps of undesirable foreground pixels quite effectively, it has the big disadvantage that it will affect all regions of foreground pixels indiscriminately. Opening gets around this by performing both erosion and a dilation on the image.

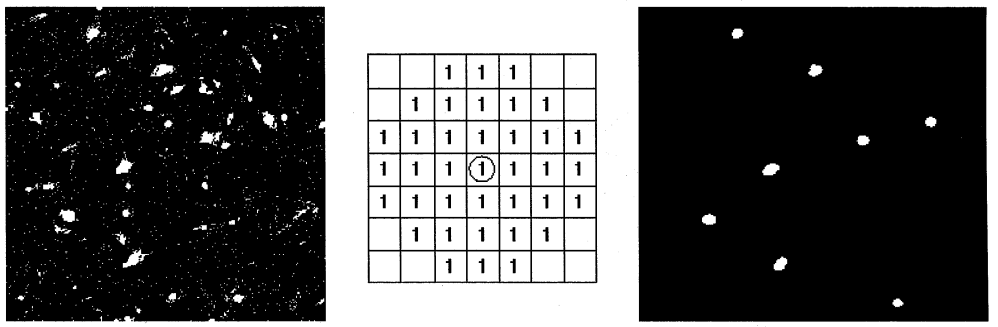

Figure 3: Opening by a 7 x 7 circular structuring element

### 3.1.4 Closing

Closing of A by B is obtained by the dilation of A by B, followed by erosion of the resulting structure by B,

$$A \bullet B = (A \oplus B) \ominus B$$

One of the uses of dilation is to fill in small background color holes in images. One of the problems with doing this, however, is that the dilation will also distort all regions of pixels indiscriminately. By performing erosion on the image after the dilation, i.e. a closing, it reduces some of this effect.

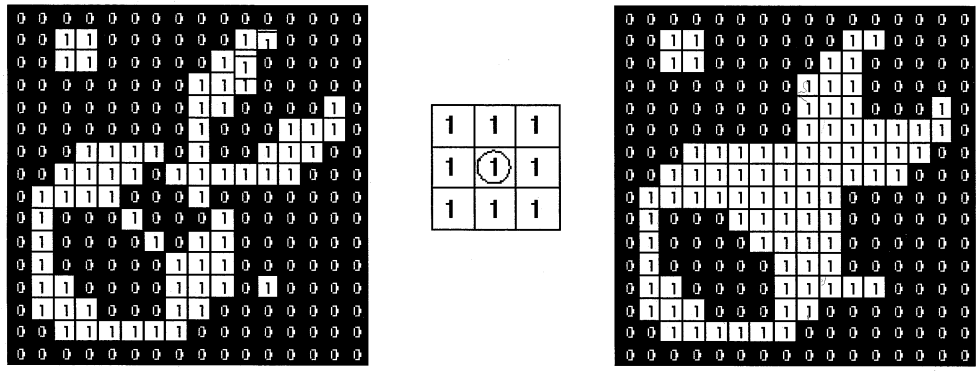

Figure 4: Closing by a 3 x 3 structuring element

In this research, an opening operation is performed with a structuring element size of 5 to reduce the noise level of the dataset.

## 3.2 Colon Wall Detection

After the lumen has been detected, the initial curves required by active contour model are established. The colon wall is segmented using active contour segmentation techniques with the initial curves in the previous step.

Active contour models, also called deformable models, provide a robust foundation for the representation, simulation, and manipulation of complex

non-rigid anatomical structures [39]. The potency of deformable models stems segmentation of anatomic structures by exploiting constraints derived from the image data together with a priori knowledge about the location, size, and shape of these structures. In recent years, deformable models based image segmentation has seen emergence of two competing approaches – Snakes and Level sets.

Snakes [40] can be viewed as *Lagrangian* geometric formulations wherein the boundary of the model represented in a parametric form. The minimizing energy along a curve embedded roughly around the object of interest is derived. The deformation energy function is minimized with 'internal' and 'external' energies along its boundary. The geometric information is considered as an internal energy and image gradients as an external energy. The models act like elastic bodies that stabilizes at the deformation energy function is minimized. The drawback of these approaches is a good initialization step is required, later improvement of the model can adopt topological changes. [41] The other type of active contour models using *Eulerian* framework called level set methods.

Level set methods [42, 43] provide a mathematical formulation for tracking the motion of curve including optimal path planning which can be recasted as front propagation problems. The evolving constraints for propagation of interface can be defined in problem domain by exploiting constraints derived from the image

data together with a priori knowledge about the location, size, and shape of these structures. The advantages of this approach include the ability to evolve the model in the presence of sharp corners, cusps and changes in topology.

Level set method for image segmentation has been extensively evaluated over the last few years. Level set model uses a function that depends on the image gradient, as an edge detector to stop the curve evolution [43, 44]. The model can only detect objects defined by gradient. This type of segmentation by using only local information has been often frustrated by poor-contracted regions due to occluding and occluded objects and often enhanced by their use of prior shape information. Geometric shape models provide extrinsic information about an object and can be incorporated explicitly especially for medical image segmentations where prior shape information can be collected. Human beings view an object's appearance in an image by both its shape and by the view of the object. Shape is a powerful property for distinguishing an object from its surroundings in an image and should be used to complete the information provided by local properties of the image.

A model using level set and shape prior has been developed to detect objects occluded in an image [37, 38, 45]. Texture information applied to level set [46] has also been reported with good results and should be explored for polyp detection.

The general idea behind the level-set method is to apply a function $\phi(p,t)$ to the space the interface inhabits, where *p* is a point in the space, and *t* a point in time. The function is initialized at $t = 0$, and then a scheme is used to approximate the value of $\phi(p,t)$ over small time increments.

The first step in applying the level-set method is to pick a mesh, or a grid of points that covers the image. In general, the finer the mesh, the more accurate the level-set method is. Once a mesh is chosen, the next step is to initialize the value of $\phi(p,t)$ at each point of the mesh. For any point *p* in the mesh, which in the CT data is a pixel in the image, the function $\phi$ is defined as follows,

$$\phi(p,t) = \pm d$$

Where *d* is the distance from the point *p* to the curve at the time $t = 0$. The positive sign is used if the point *p* is outside the closed curve, while negative if the point *p* is inside. Thus the name of the level-set method is explained: at any time $t_0$, the evolving curve corresponds to the locus of all points p such that $\phi(p,t_0) = 0$, and that locus is a level curve of the $\phi$ function. The locus of all points *p* such that $\phi(p,t_0) = c$, contour around the original curve, where *c* is an arbitrary positive or negative constant.

Clearly, as the curve evolves in time, the value of the function $\phi$ at each mesh point evolves too. The rest of the level-set method consists of updating the

value of function $\phi$ at each point using a good scheme over small increments of time.

To illustrate the concept in another way, the level set approach takes the original curve, the black one on the left below, and builds it into a surface. That cone-shaped surface, which is shown on the right below, has a great property; it intersects with the *xy* plane exactly where the curve sits. The surface on the right below is called the level set function, because it accepts any point as input in the plane and hands back its height as output. The black front is called the zero level set, because it is the collection of all points that are at height zero.

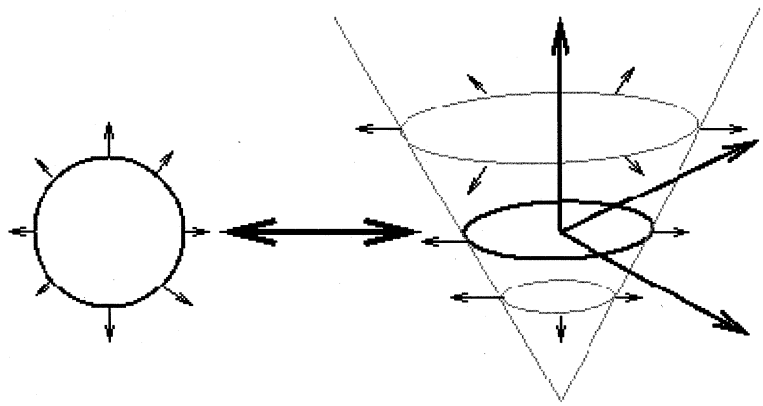

Figure 5: Level-set method

Imagine a saw that can cut a perfectly leveled slice of the surface and then drop it onto the *xy* plane.

- If the saw cuts the level set surface at height zero above the *xy* plane, the ring that will drop to the *xy* plane will be the original black front.
- If the saw cuts at some other height, a different ring will drop down, producing one of the grey curves instead.

The idea is that instead of moving the red front, one might try and instead move the surface on the right. In other words, the level set function expands, rises, falls, and does all the work. To find out where the front is, get out the saw and cut the surface at zero height.

The initial position of the interface gives initial data for a time-dependent problem. In other words, the solution starts at a given position and evolves in time.

The level-set method takes the problem of a moving curve and trades it in for a moving surface. The reason why this is a good idea lies in that the red front at the surface on the right side can get wildly contorted, but the blue level set function is well-behaved. All the complicated problems of breaking and merging are easily handled. Better yet, everything works for three dimensional surfaces with no change.

In this research, level-set method is applied for colon wall detection after minima detection. Each level set is defined using signed distance transform on the boundaries resulting from the minima detection. The following image shows

a segmentation result on one image slice using minima detection and level set method.

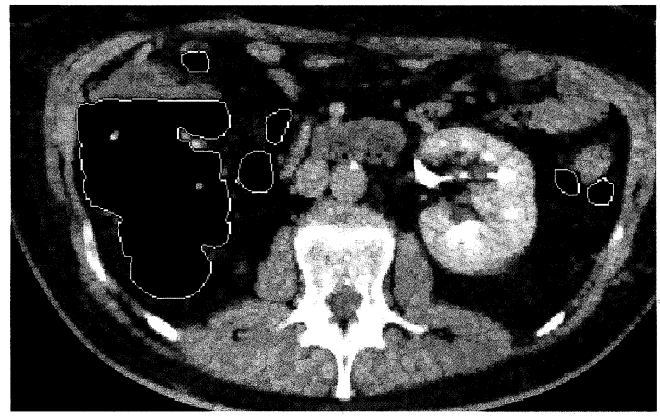

Figure 6: Initial curves segmented using active contour model

## 3.3 Polyp Detection

### 3.3.1 Curve Detection

Identifying colonic polyps using CAD is very challenging because polyps occur in various sizes and shapes, and because of thickened folds and retained stools may mimic their shape and density.

In this research, curvature detection is achieved by using a computer-graphics based light-weighted detection mechanism that not only speeds up the overall detection process, but also suits the manual navigation system.

A digital image, or a raster graphics, is a data structure representing a generally rectangular grid of pixels viewable via a computer monitor, paper, or other

displaying medium. Images viewed on computer screens are dimensioned in pixels, screens are dimensioned in pixels, and video systems show pixels directly. This implies that, the angle between two adjacent pixels in a digital image can only be either 45, or 90, or 180 degrees. There are no other possible values in between.

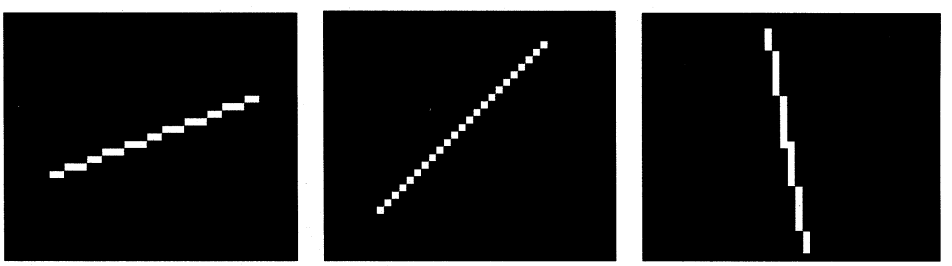

Figure 7: Angles in raster graphics

Based on this fact, the task of polyps-detection is mainly to pinpoint the sharp turning points that could possibly lead to polyp candidates. The whole process is illustrated as follows.

First of all, mark all the pixels where direction changes happen. This means, for any two pixels in the segmented colon wall, draw a straight line between them. If the line makes a perfect horizontal, vertical or 45 degree diagonal, the pixels in between will not cause the curve to change direction, and will be discarded. The following example illustrates a result of this step. The white dots represent the pivots where direction changes occur around them.

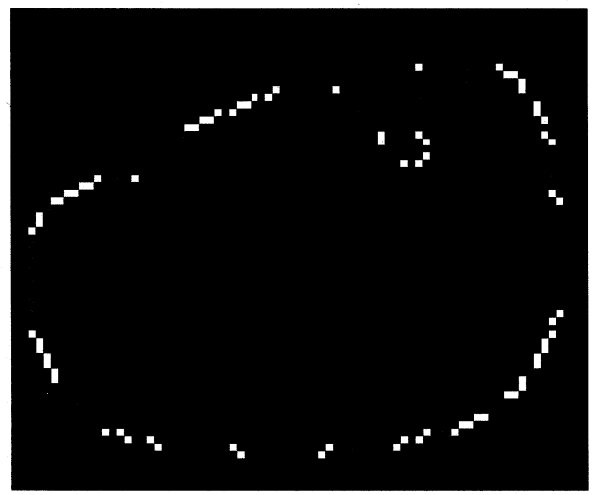

Figure 8: Directional changes

Next, remove continuous marks, but keep the first one only for next cycle of processing.

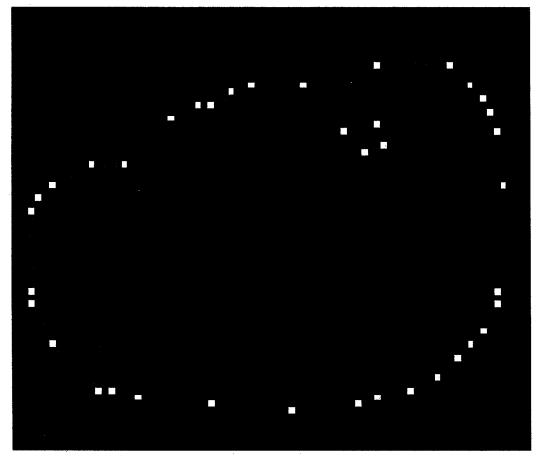

Figure 9: Simplified directional changes

In this step, keep the pixels that sharp turns happen around them. This is done by selecting three highlighted pixels, and calculating the angle of the two line segments between them. A threshold is applied to determine what kind of angle qualifies a sharp turn. In this study, 40 degree is selected as the threshold, any

thing bigger than that will be considered a sharp turn.

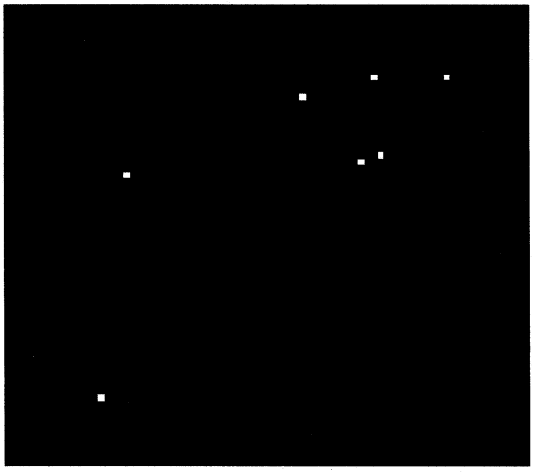

Figure 10: Sharp turns

Further more, left-turn and right-turn marks are identified. An iteration process will go through all the marks in turns to access whether it serves as a central point for a left or right turn among three consecutive marks. In the following example, the white dots represent left-turn marks, while the dark gray ones characterize right-turn ones.

Figure 11: [left-turn, right-turn] pairs

The last step is to enumerate all possible [left-turn, right-turn] pairs to identify potential polyp candidates. If the number of pixels in the curve within the [left-turn, right-turn] range is greater than twice the distance between them, the curve segment in [left-turn, right-turn] will be regarded as a polyp candidate.

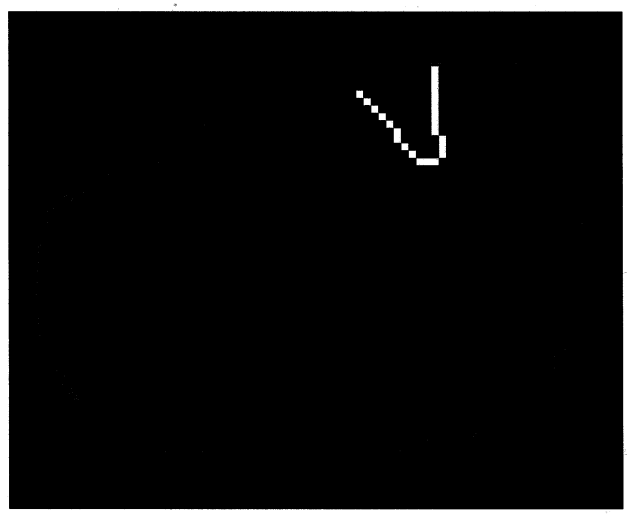

Figure 12: A polyp candidate

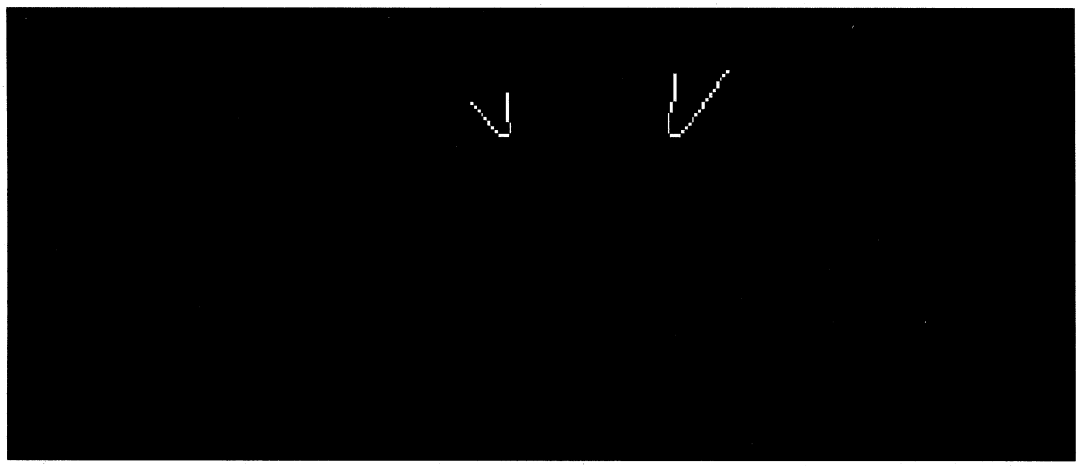

Figure 13: Result of polyp detection

### 3.3.2 Flat polyp Detection using Texture Analysis

After the segmentation step, the surface of the colon can be detected and the

gray scale information inside the colon can be abstracted and analyzed. For example, the textures for different features that reside in the colon can be classified; stool or polyps can be distinguished with good accuracy. This will improve the detection rate compared with methods that only use surface shape information to characterize the polyps. The textures between polyps and stool are different in nature. Polyps appear in grayscale with more homogeneity, while the grayscale of stool varies in large scales.

A morphological operation called directional dilation can be utilized to dilate the object on the positive norm direction of the curve that represents the colon wall. The dilated region can then be used as the mask of the colon wall. Texture analysis will be applied on this thick region for search polyp candidates. This step helps us to analyze the texture information around the polyp candidates and allows us to detect the abnormality appearance of the polyp candidate not only by its shape, but also by its texture information. Adding texture analysis is more effective for detecting the flat polyps, which can only be achieved by looking at the abnormality of texture information on the detected thick region. To date, there is no literature that addresses the flat polyp detection. Texture analysis also helps distinguishing stools from polyps inside colon walls. Polyps usually appear in grayscale with more homogeneity, while the grayscale of stools varies in large scales.

The result from direct dilation is a thick ring around the colon wall. The thick ring is made semi-transparent, and the original CT image is placed underneath. By doing so, it's easy to examine the area within the ring for abnormality, such as particularly dark texture as the normal appearance of flat polyps.

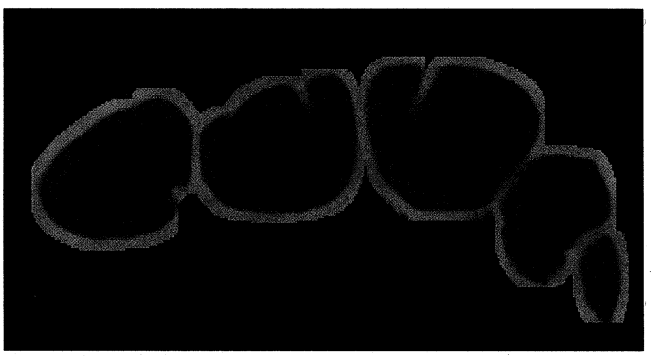

Figure 14: Texture analysis

## 3.4. An Innovative Viewing System

Development of the 3-Component Viewing System is an essential part of our strategies to increase the overall accuracy of CT Colonography. A solution is provided in which the 3 major components of this viewing system work as a single tool to reduce the false-negative rate by ensuring the complete examination of the colonic mucosa, including the "blind areas" during the colonic fly-through of CT Colonography. These components consist of:

### 3.4.1 Mucosal Coloration

Mucosal Coloration is a technique that provides a simple, automated process that converts the color of unviewed colonic mucosa from one shade or hue to another, as the mucosa is adequately observed.

To ensure adequate observation, in this study, as a portion of colonic mucosa is viewed, at a specified distance and angle of view (DAV), it would be transformed into a different shade or color (e.g. from yellow-tinted to pink). Thus, any portion of the colonic mucosa that was not viewed in the required field of view would remain yellow-tinted. The optimum DAV would then be investigated as an integral part of this study.

### 3.4.2 Front-and-Side-Viewing Colonoscope

False positive or false negative results, i.e. misidentification or failure to detect polyps could occur. The 3-component viewing system built into this project provides a means of guaranteeing that all surfaces of the colonic wall are adequately examined, thus serving as an internal quality assurance mechanism to reduce the incidence of false negative results.

There are two types of endoscopes used by gastroenterologists: forward-viewing scopes and side-viewing scopes. Virtual Colonoscopic Fly-Through is generally displayed as if it is seen through a forward-viewing endoscope. The "virtual colonoscope" described here is capable of both

"front-viewing" for most of the fly-through, as well as "side-viewing" for looking around mucosal folds, at "blind areas". The front-view or side-view option is selected by the observer during the course of the examination, as needed.

### 3.4.3 Navigation System

Virtual navigation system, a computerized medical procedure for examining tubular organs, has been increasingly considered as an alternative method for medical diagnosis and treatment. A virtual fly-through inside the tubular human organs is less invasive, safe and cost effective for medical examination and surgical planning. The virtual exploration through patient-specific data assists immensely radiologists to perform a diagnosis without physical operations on the patient. Surgical diagnosis and planning can also be done with reduced patient discomfort.

When harnessing the virtual colonoscopy system as a tool for detecting colon polyps, it is a common practice to engage with automated fly-through based on the paths generated automatically. In the case of automated fly-through inside the colon, some "blind spots" will occur at backs of folds and can be missed out by the virtual camera.

In this research, we propose a virtual colonoscopy navigation system based on human-computer interaction. The method identifies the path of the virtual

cameras for a fly-through within the segmented colon, which is carried out by means of level-set method above-mentioned. Two virtual cameras are deployed in the navigation system, a front-view camera, and a side view one. The front-view camera path is selected as the geometric center of the colon walls. It flies through the 3D colon model.

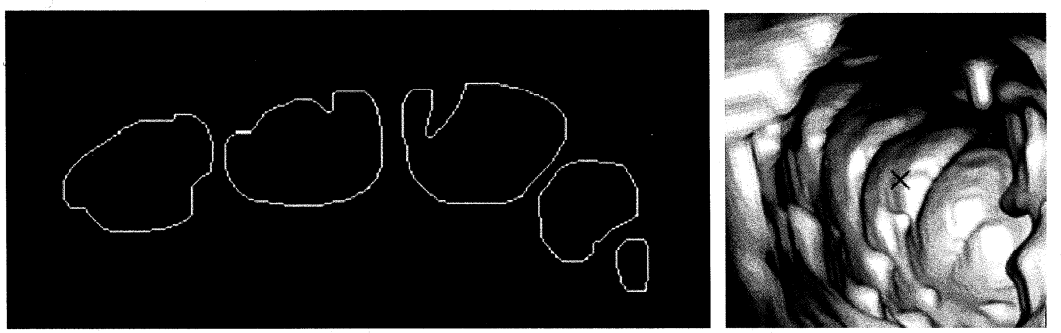

Figure 15: Front-view camera path

In order to address the "blind spots" issue, a side-view camera is added to the navigation system. The side-view virtual camera sits at the same location as the front-view one, and is always perpendicular to the fly-through direction. It can be rotated side way in order to scan the surrounding regions.

Both cameras are controlled by human viewers, using Up and Down arrow keys to control the fly-through of the front-view camera, and Left and Right arrow keys to rotate the side-view camera around the fly-through direction.

As the virtual cameras fly through the model, the navigation system keeps track of the position of the virtual cameras inside the model, displays the front-view

on one window, and side-view on another. The advantage of virtual exploration is that the surgeon can noninvasively perform a diagnosis and mark the position of potential polyps for surgical planning.

Because the movements of cameras are controlled by user inputs, expensive processing of finding optimum fly-through path can be alleviated, and the navigation system is computationally efficient to deal with large and complicated 3D Colon data.

The experimental results showed that about 20% of colon regions were classified as unobserved region in every fly-through exploration.

# 4. Experimental Results

A software system is designed and developed using Microsoft Visual C++, along with Amira and VTK. Amira is a powerful, multifaceted software platform for visualizing, manipulating, and understanding life science and bio-medical data. And Visualization Toolkit (VTK) is an open source, freely available software system for 3D computer graphics, image processing, and visualization.

## 4.1 Architecture

The flowchart blow demonstrates the architecture of the system, and outlines the major steps involved in the whole process.

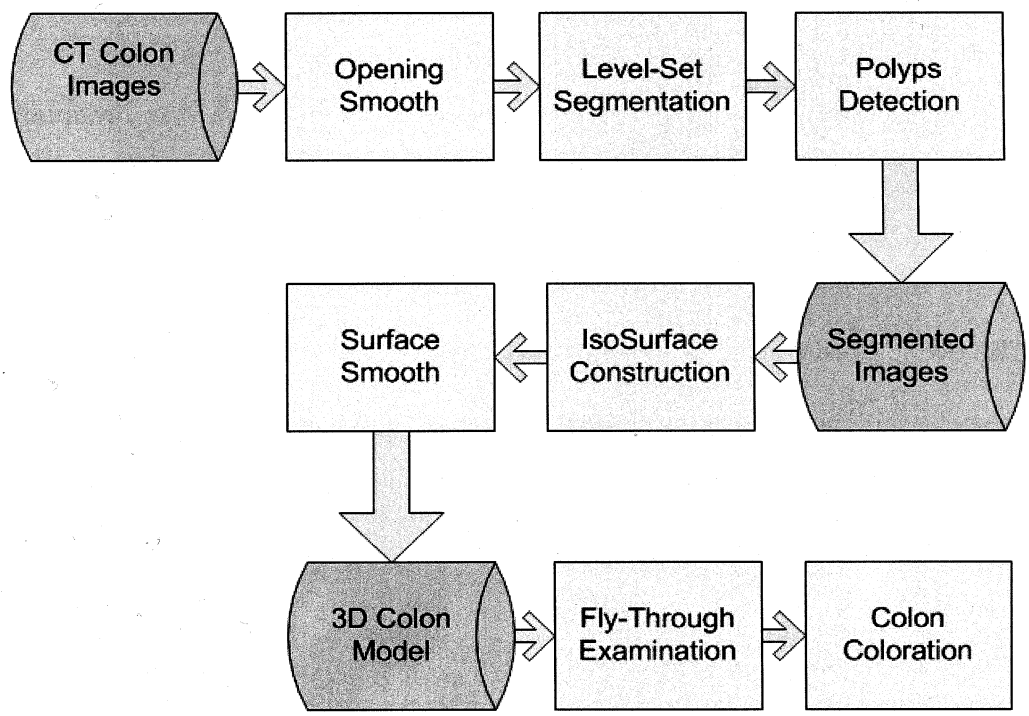


Figure 16: Software system architecture

The input data (CT Colon Images) first goes through morphological opening smooth, then is segmented by level-set method, and later undergoes polyp-detection procedure. The output is segmented colon data.

The segmented CT images then are built in to an IsoSurface, a 3D model ready for fly-through examination. Then smoothing is applied to remove small rugged regions for better viewing experience.

The 3D colon model is then loaded into an application written in VTK for fly-through examination and colon coloration.

## 4.2 Test Results

We have collected 10 CT data sets of patient abdomen. The segmentation results and surface generation are demonstrated in the figures follow:

The two figures below show a typical CT image(s) as input data.

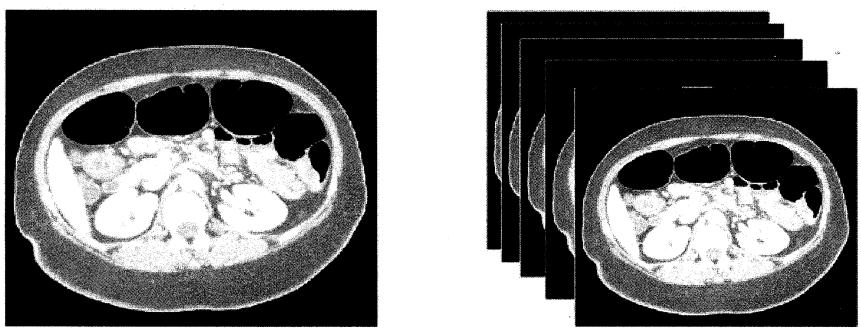

Figure 17: (a) A typical colon image, (b) A stack of CT colon images

The following figure displays the segmentation result of a CT image using level set method.

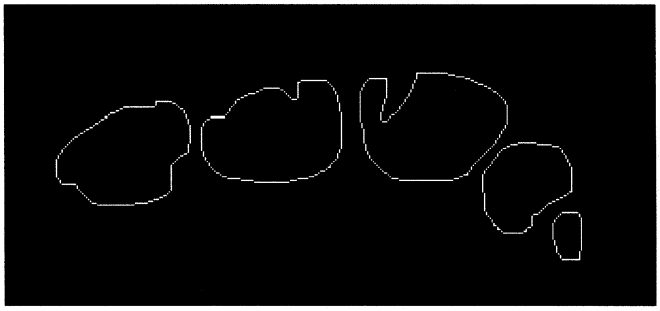

Figure 18: Segmentation result using level-set method

Overlapping the segmented image with the original CT image creates a new image as shown below. It is safe to say that the segmentation result is accurate.

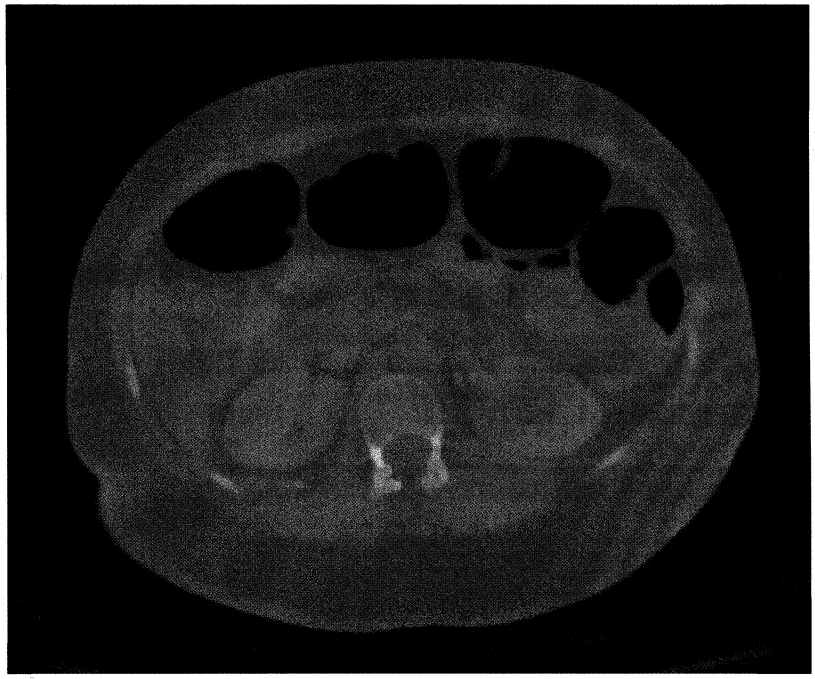

Figure 19: Segmented result overlapped with the original image

The segmented CT images are then loaded into Amira, and an IsoSurface is then constructed. In addition, the surface goes through a smoothing process to

remove small rugged regions. The surface construction result is a 3D colon model ready for fly-through examination.

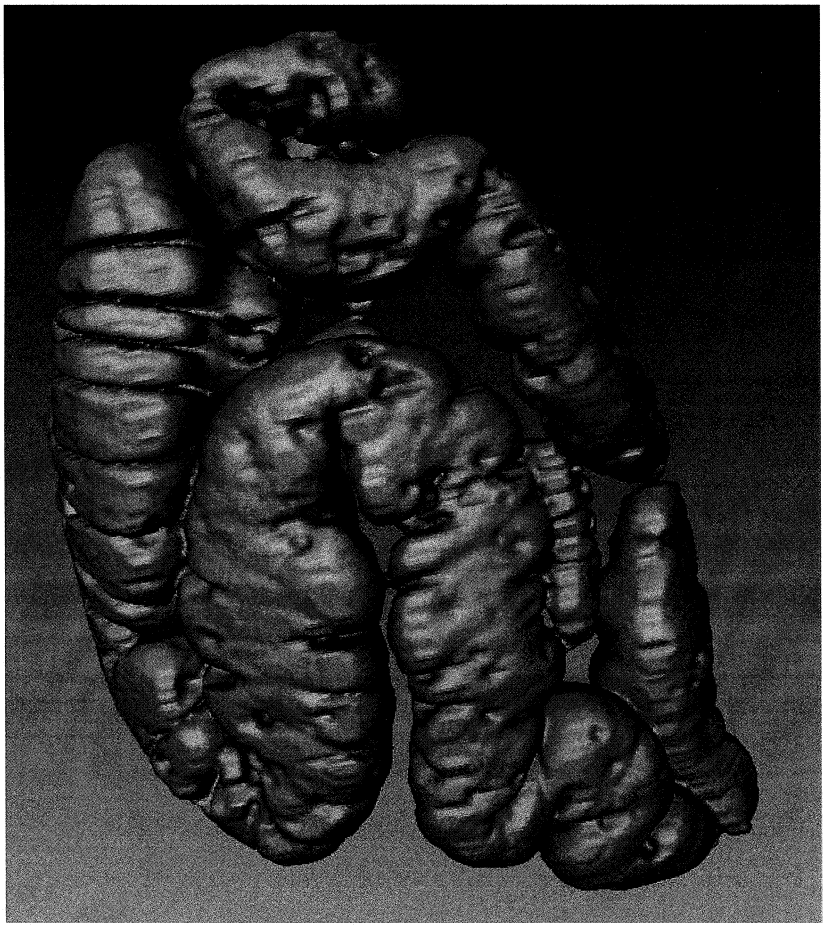

Figure 20: 3D colon image

The following image represents an inside view of the 3D colon model.

Figure 21: Inside-view of a 3D colon model

The 3D colon model is then loaded into an application written by VTK for fly-through examination, which is done by manually controlling the position and orientation of the front-view and side-view cameras. The image below gives an impression of what a coloration result looks like.

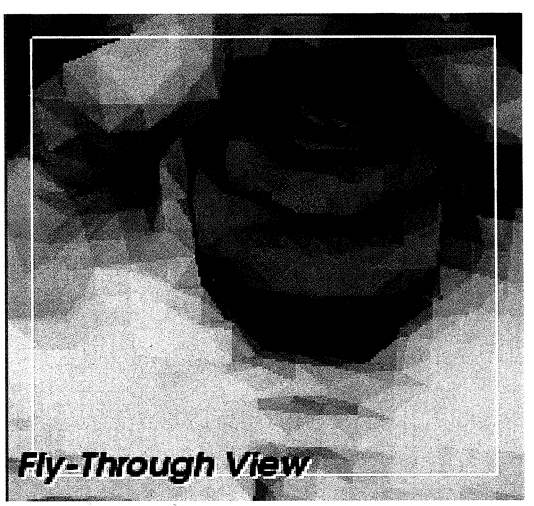


Figure 22: Mucosal coloration during fly through,
viewed regions shown in light color, while unviewed dark

The coloration is a real time process, and is done as the cameras move back and forth or sideway. It is a rather computational expensive operation. In order to speed up the fly-through process, the 3D colon model is scalded down first to decrease the number of triangles there are in the IsoSurface. This results in a loss of image quality but immensely increases the coloration process and augments the smoothness of fly-through examination.

By setting up the viewing distance of the front-view camera, the unviewed region remains in its original color, blue in this example. The viewed one, instead, is transformed to a different color, green in this case. In this way, the unviewed region in the far distance will be highlighted. The "blind spots", which are not visualized by the cameras remain in blue, their original color as well.

# 5. Summary

## 5.1 Conclusion

This research proposal provides a comprehensive computer-processing methodology for the CAD component of CT Colonography. The system under development has been designed to find solutions to specific clinical problems, through the application of computer graphic technology. The individual techniques that are under development are integrated into a cohesive and complete methodology that specifically addresses, and provides solutions to, the limitations of CT Colonography as documented in the medical literature.

The overall performance of the segmentation method is satisfactory. The segmentation methodology described here also provides solutions to other clinical problems. Our system improves the existing systems by searching more detailed information to classify polyps, provide a 100% surface coverage viewing utility, and improved the accuracy of the polyp detection.

## 5.2 Future Work

Polyp detection needs to be enhanced to detect polyps smaller in size (less than 3 mm). More polyp samples need to be collected. Computation speed can also be improved.

In order to overcome the "blind-spot" issue, the current control method for fly-through was purposely designed as a manual control system. Which means, views are in total control of both front-view and side-view cameras. It is convenient in a way that human viewers have great latitude of manipulating the positions and orientations, and the fly-through velocity of the cameras. However, a semi-automatic control system should provide a richer experience in fly-through examination.

In addition, an innovative idea of flat-side-view has been raised in the course of the project development. The approach is to capture the colonic surface surrounding the side-view camera and flatten it to a 2D image. In this way, it makes possible to examine the folded colon regions without even having to rotate the side-way camera.

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