Virtually Assisted Optical Colonoscopy

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ABSTRACT

We present a set of tools used to enhance the optical colonoscopy procedure in a novel manner with the aim of improving both the accuracy and efficiency of this procedure. In order to better present the colon information to the gastroenterologist performing a conventional (optical) colonoscopy, we undistort the radial distortion of the fisheye view of the colonoscope. The radial distortion is modeled with a function that converts the fisheye view to the perspective view, where the shape and size of polyps can be more readily observed. The conversion, accelerated on the graphics processing unit and running in real-time, calculates the corresponding position in the fisheye view of each pixel on the perspective image. We also merge our previous work in computer-aided polyp detection for virtual colonoscopy into the optical colonoscopy environment. The physical colonoscope path in the optical colonoscopy is approximated with the hugging corner shortest path, which is correlated with the centerline in the virtual colonoscopy. With the estimated distance that the colonoscope has been inserted, we are able to provide the gastroenterologist with visual cues along the observation path as to the location of possible polyps found by the detection process. In order to present the information to the gastroenterologist in a non-intrusive manner, we have developed a friendly user interface to enhance the optical colonoscopy without being cumbersome, distracting, or resulting in a more lackadaisical inspection by the gastroenterologist.

Keywords: Virtual Colonoscopy, Optical Colonoscopy, Radial Undistortion, Distortion Correction, Centerline Extraction, Shortest Path

1. INTRODUCTION

Colorectal cancer is the second leading cause of cancer-related mortality in the United States [10]. As with many cancers, early detection is key to a successful treatment of the disease, and screenings are recommended to detect suspicious polyps inside of the colon. Traditional colon screening has been performed using an optical colonoscopy (OC) procedure, requiring uncomfortable bowel preparation and sedation, and accompanied by a risk of complications from the procedure. During the past decade, virtual colonoscopy (VC) techniques have been developed to utilize computed tomography (CT) scans of the abdomen in screening for colonic polyps. VC is noninvasive, and allows for a digital, rather than physical, cleansing of the bowel. These VC procedures have been demonstrated to be as or more effective than OC procedures in identifying cancerous polyps [6, 9]. More recently, methods for the computer-aided detection (CAD) of colonic polyps from CT data have been developed which can perform with high sensitivity (demonstrated up to 100%) and a low rate of false positive results [3, 4].

Even with technological strides being made towards fighting colorectal cancer, there has been reluctance among some doctors and insurance companies to adopt the use of the VC technology that has been developed. It has been demonstrated, however, that OC is unable to obtain the same coverage of the colon lumen as VC, with the OC missing approximately 23% of the colon surface, while a standard VC examination would miss only about 9% of the surface [5]. Tools built into a VC system, combined with CAD techniques, would allow for a theoretical 100% coverage of the colon surface. On the other hand, OC does present some advantages over VC, in that the doctor is able to observe the color of the colon walls, as well as any blood vessels or other features on the colon surface, and perform polypectomy, if necessary. From this comes the need for a system that will merge the information from the VC into the OC procedure, allowing gastroenterologists to leverage the advantages of both techniques. Such a system would allow for a more efficient and accurate inspection of the colon by doctors searching for colonic polyps.

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The images obtained in OC are captured through a fisheye lens, which causes a high level of radial distortion in the image. Radial undistortion of these images would yield a more normal perspective view, in which the size and shape information from the inside of the colon will be more correctly presented. Since decisions on whether an item on the colon wall is a polyp or not is heavily dependent on size and shape characteristics, this would allow for an improvement in the gastroenterologist's ability to correctly identify potentially cancerous polyps. There has been much research devoted to radial undistortion, with methods using images captured with calibration grids [1, 2, 11] and methods using strictly numerical approaches [7, 8]. In order to maintain an easy to use system, it is best to avoid the need to capture images with calibration grids, and hence a simple numerical method is needed. We know of no such simple method specific to colonoscopic images.

Integrating the information from a CAD system can help to ensure that the gastroenterologist does not miss investigating critical sections. This is not trivial, as the exact path of the physical colonoscope is not known. A basic approach is to estimate this path, and correlate it to the centerline calculated for VC. The distance from the rectum along the path can then be matched to a point on the VC centerline.

2. METHODS

Being a pioneering work on some technologies necessary for a VC assisted OC system, the two techniques explored are distinct, and are discussed individually. First we will discuss our method for undistorting the radial distortion from the fisheye view of the colonoscope. We will then discuss our method in correlating the centerline of the VC to the path taken by the colonoscope in the OC.

2.1 Radial Undistortion

Radial distortion can be represented using an infinite series, with the distortion then calculated using the equation [7]

$$F(r) = rf(r) = r(1 + k_1 r^2 + k_2 r^4 + k_3 r^6 + \cdots)\,, \tag{1}$$

where $r^2 = x^2 + y^2$, with (x, y) being the normalized undistorted projected points in the image frame, and k_n are the scalar distortion coefficients. The distorted coordinates in the camera frame can then be calculated as

$$p_d = p_u \cdot f(r)\,, \tag{2}$$

where p_u are the undistorted coordinates (x_u, y_u) and p_d are the distorted coordinates (x_d, y_d) in the camera frame. It has been found that because the image space, where the work will be performed, contains noise, modeling the distortion above the second distortion coefficient does not improve the results [8], so the distortion can be modeled as

$$f(r) = 1 + k_1 r^2 + k_2 r^4\,. \tag{3}$$

It has also been found that the r values can be reduced [7], such that the distortion can now be modeled more simply as

$$f(r) = 1 + k_1 r + k_2 r^2\,. \tag{4}$$

Using this simplified model, the edges of the undistorted image are less prone to distortion artifacts from the image inverting back in on itself.

We are working in the image space, not in the space of the camera frame, so we want to calculate the distortion in the (u, v) space of the image, rather than in the (x, y) space of the camera frame. The distortion in the image (u, v) space can be calculated as

$$u_d - u_0 = (u - u_0) f(r),$$
$$v_d - v_0 = (v - v_0) f(r), \quad (5)$$

where (u, v) are the image coordinates of the original undistorted image point, (u_d, v_d) are the coordinates of the corresponding distorted image point, and (u_0, v_0) are the coordinates of the image center. The adjustment using the image center coordinates is necessary to ensure that the radial distortion occurs around the center of the image, since the (x, y) coordinates of the pixels will be in the range [1, width] for x and [1, height] for y, with the center point being at (width/2, height/2). In the camera frame, the coordinates (0, 0) are at the center, with the values for x in the range $[-x, x]$ and the values for y in the range $[-y, y]$, and hence no adjustment would be necessary.

In calculating the distortion, it is necessary to calculate the value of r, used in the equation for $f(r)$ (Equation 4). Since $r^2 = x^2 + y^2$, this value must be calculated in the 2D projection space of the camera frame, not in the image space. This is accomplished using the affine transformations

$$x = \frac{u - u_0}{m_u}, \quad y = \frac{v - v_0}{m_v}, \quad (6)$$

where m_u and m_v are the number of pixels per unit distance in the u and v direction, obtained from our previous work in colonoscope calibration [5].

The typical method to undistort an image using these formulae is to solve for the undistorted (u, v) values for each pixel (u_d, v_d) in the distorted image. We perform the undistortion on the graphics processing unit (GPU), using the coordinates of the framebuffer as the output for the undistorted image. Because of this, the problem can be thought of as knowing each pixel location on the undistorted image, and from there calculating where on the distorted input image to obtain the color value from. Using this method, the values for (x, y) in Equation 6 can be easily calculated. Likewise, the distorted pixel locations (u_d, v_d) can be easily calculated using Equation 5 as follows:

$$u_d = (u - u_0) f(r) + u_0,$$
$$v_d = (v - v_0) f(r) + v_0. \quad (7)$$

The undistorted image is also formed to be larger than the original, distorted image, as the undisortion pushes the image information past the boundaries in the distorted image.

Rather than locking the scalar distortion coefficient values for k_1 and k_2 to specific values or necessitating individual colonoscopes to be calibrated before use to obtain these values, we provide a simple interface with two thumbwheels to allow for easy adjustment of the two values. Since barrel distortion (the type of radial distortion present in colonoscopes) occurs when the value of $k < 0$, the thumbwheels should be adjusted to negative values to perform the undistortion.

2.2 Path Correlation

In addition to the ordinary centerline that is calculated for VC, we also calculate a hugging corner shortest path. This approximates more closely the actual path of the physical colonoscope that is snaked through the patient's colon [4]. An example of the difference between the conventional centerline that is calculated for VC and the hugging corner shortest path that we calculate to approximate the physical colonoscope is shown in Figure 1. Figure 2 shows the location of the lens on the distal end of a colonoscope (other items on the distal end are not shown). Because the lens center is not directly on the edge of the distal end, the hugging corner shortest path will always remain some minimum distance from the colon wall, never exactly touching the colon surface. This distance can range (in our example colonoscope) from 2.8 mm to 10 mm, depending on how the colonoscope is oriented, with the average distance being 6.4 mm.

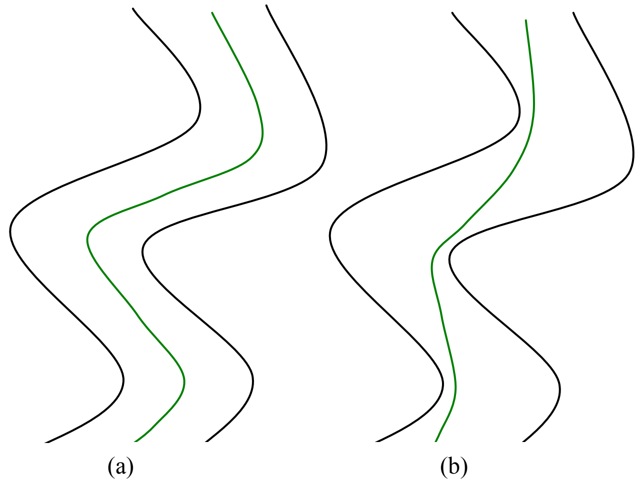


Figure 1: (a) An example of a centerline, and (b) a hugging corner shortest path.

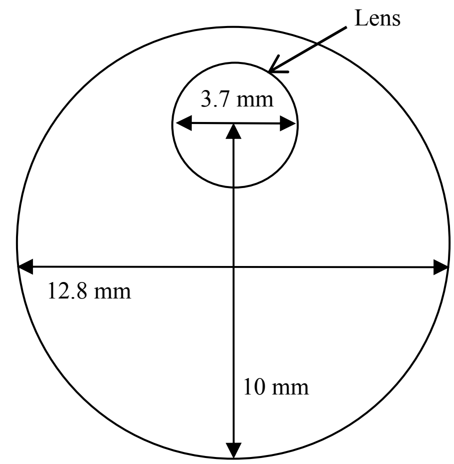


Figure 2: The location of the lens on the distal end of a colonoscope.

The centerline and shortest path are both represented as spline curves, and are discretized into a certain number of points for display and visualization. Knowing what distance the colonoscope is inserted, the discrete point for that location on the shortest path can be calculated. The centerline is correlated to the shortest path so that any point along the centerline in the VC can be matched to a point on the shortest path in the simulated OC (and vice versa).

The idea of the path correlation is that for each point on one path, a corresponding point on the other path can be found such that the views inside the colon generated from both of these points should be similar. For this, simply finding the nearest point on the other path is not appropriate, as the bends in the paths might make a physically closer point be further away from the area of interest. Rather, we want to find matching points that are in the same cross section of the colon lumen.

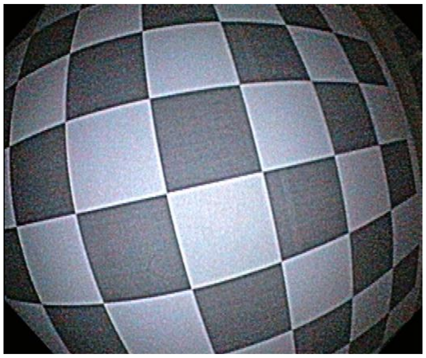
Since the centerline follows the contours of the colon more closely than the shortest path, we use it as the starting point in calculating the correlation. The normalized direction of the centerline at a point x is obtained using the next and previous points on the centerline. To ensure a smooth curve for this calculation, several points before and after x are averaged and used to calculate the direction vector. This normalized direction vector is then taken to be the normal of a plane that is perpendicular to point x. Since the centerline closely follows the contours of the colon, this plane can be said to approximate the cross section of the colon which contains point x. We then find the nearest point to x on the shortest path which is within some tolerance of being on the plane. This point y on the shortest path is then also in the same cross section as point x. Since they are in the same cross section, points x and y can be considered correlated.

3. RESULTS

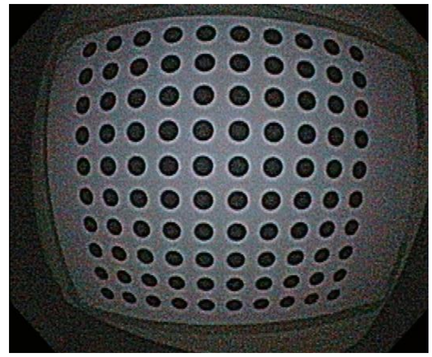
We evaluated our methods using simulated data to illustrate that they work as expected. For the radial undistortion, this means using images captured through colonoscopes. For the path correlation, we used CT volume data to extract the paths and then test that the correlation method will correctly generate matching views.

3.1 Radial Undistortion Results

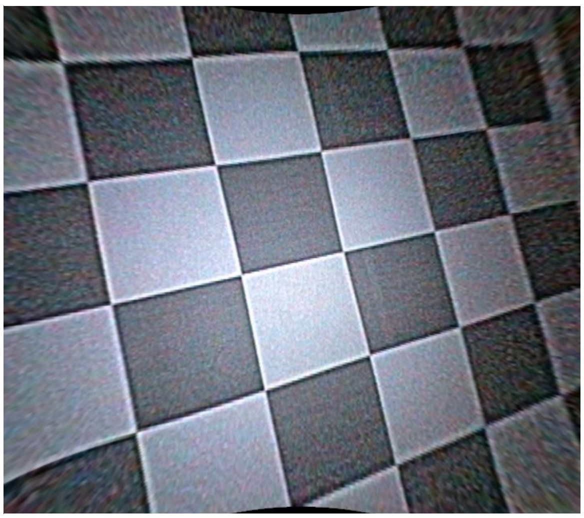
We tested our undistortion technique on still images captured through an Olympus (Center Valley, PA) colonoscope Model CF-Q160L with a field of view of 140 degrees. The images were acquired of boards with regular geometric patterns on them (such as a checkerboard), so that the effectiveness of the undistortion algorithm could be clearly seen. Figure 3 shows examples of performing our undistortion technique on two such images. The radial distortion can be readily observed in image 3(a), where the square boxes of a checkerboard have become warped, with the straight lines being curved. In the undistorted images 3(c) and 3(e), the lines have been straightened and appear as when viewed normally in perspective space. The undistortion technique was also applied to image 3(b), with similar visual results.



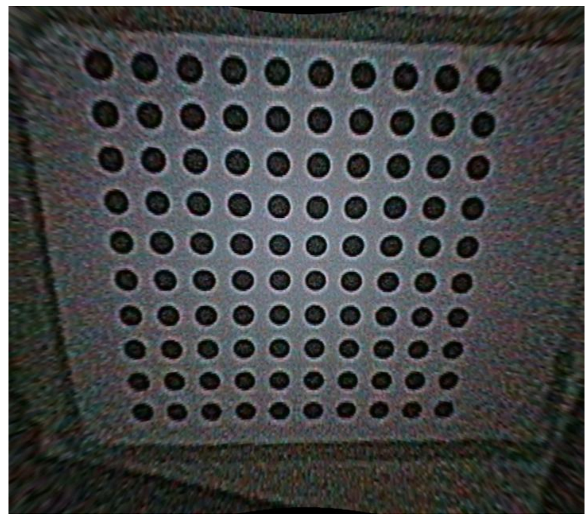
(a) Original distorted image from colonoscope.



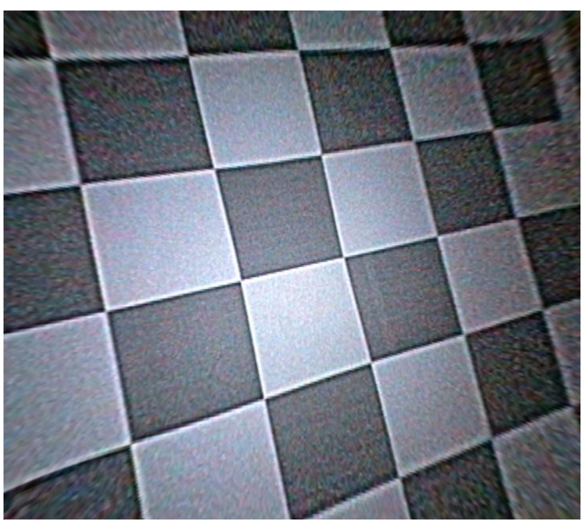
(b) Original distorted image from colonoscope.



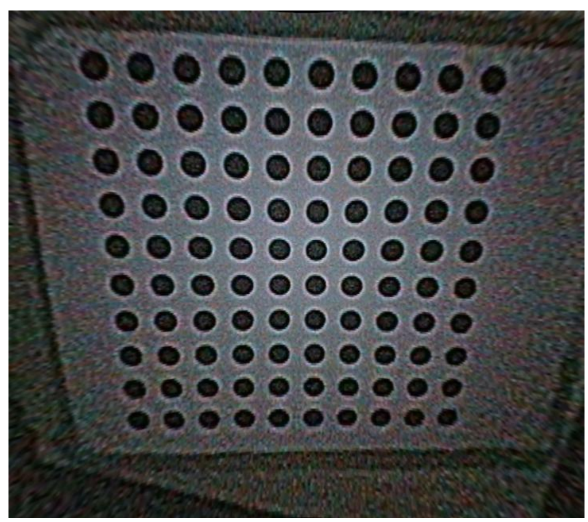
(c) Undistortion of image (a) with parameters k_1 = -0.024000 and k_2 = 0.000000.



(d) Undistortion of image (b) with parameters k_1 = -0.024000 and k_2 = 0.000000.

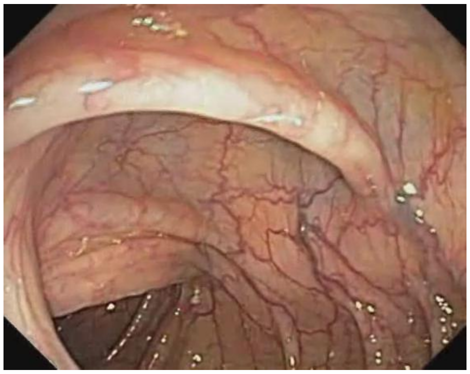


(e) Undistortion of image (a) with parameters k_1 = -0.027000 and k_2 = 0.000150.

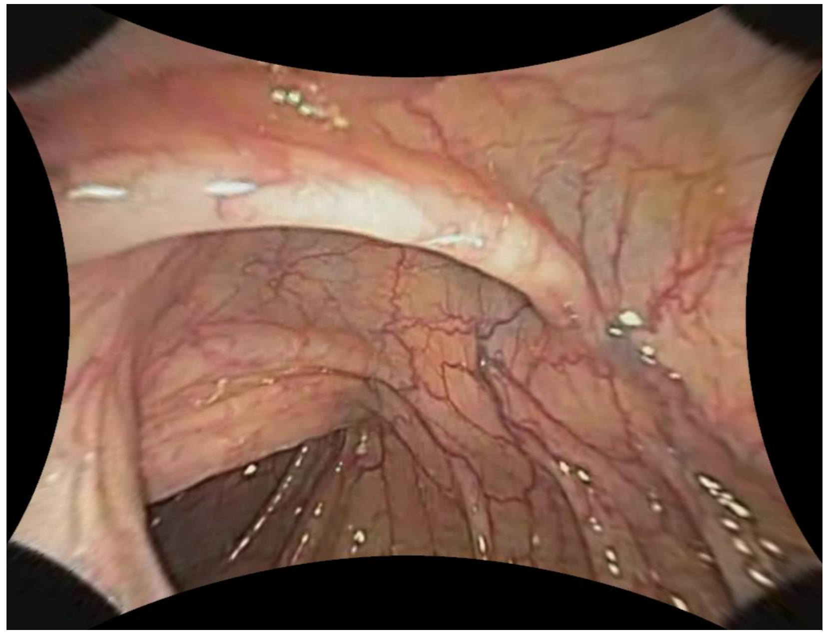


(f) Undistortion of image (b) with parameters k_1 = -0.027000 and k_2 = 0.000175.

Figure 3: Examples of performing undistortion on images of regular geometric patterns captured with a colonoscope.



(a)



(b)

Figure 4: (a) Original image of a colon wall captured with an endoscope. (b) Undistorted version of (a).

In performing the undistortion, the resulting images are larger than the original images. In essence, the center of the image (where there is very little distortion) has remained the same, while the sides have been pulled outwards. It can be noted from the undistortions that adjusting the value of k_2 in images 3(e) and 3(f) does not produce a noticeably better result than images 3(c) and 3(d), which were created with k_2 ignored (left at a value of 0.0). It can be inferred from this that the use of k_2 is unnecessary, and future tests that we performed utilized only k_1 for adjustments. Being necessary to adjust only k_1 also increases the simplicity of the system for the user.

In Figure 4, we show a result of undistorting an endoscopic image from an OC video of an NIH dataset from the Pickhardt et al. study [9]. The undistorted image in Figure 4(b) presents a perspective view more similar to what one would observe in the real world inside the colon if a fisheye lens were not used. The empty black spots at the top, bottom, left, and right are areas that fall outside of the image area in the distorted image, and hence contain no image data. These areas can be ignored, or, if they are found to be too distracting, they can be simply cropped out at the expense of losing some information from the image corners. This undistortion, as well as those in Figure 3, were created by experimentally determining the appropriate value for k_1 (and k_2 for Figures 3(e) and 3(f)) necessary to achieve the desired result.

As mentioned in Section 2.1, this radial undistortion is performed on the GPU. The speed of the GPU allows for real-time performance, so the value of k_1 can be adjusted interactively. We are able to achieve an average frame rate of approximately 35 frames per second using a 3.6 GHz Xeon PC running Windows XP Professional x64 with 4G RAM and an NVIDIA Quadro FX 4500 GPU. This real-time performance also means that it would be possible to perform the radial undistrotion on the video from the colonoscope in real-time.

3.2 Path Correlation Results

To test our path correlation method, we used the centerline and shortest path that were extracted and checked the correlation by comparing the locations of the correlated points and the views from these points inside the colon lumen. Figure 5 shows an example of the extracted centerline and hugging corner shortest path with the colon shape. It can be seen that the name "hugging corner" is appropriate, as the shortest path will stay near the bends of the colon as it curves around, "hugging" it, whereas the centerline will remain in the center of the colon lumen.

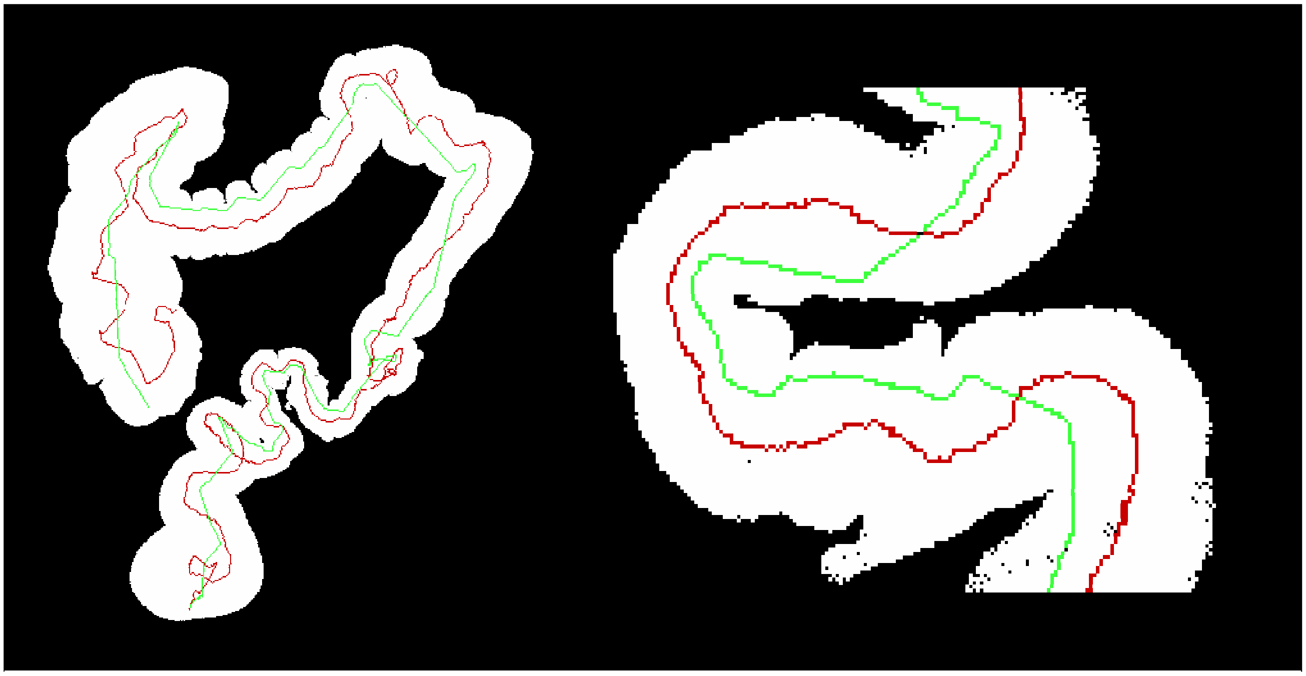


Figure 5: Example of an extracted centerline and hugging corner shortest path for a virtual colon model, showing the entire model and a zoomed in section. The centerline is represented in dark red, while the hugging corner shortest path is represented in light green.

Figure 6: Three examples of the correlation between the centerline (dark red) and hugging corner shortest path (light green). Calculated corresponding points are illustrated by a black dot on each line.

To observe the locations of the corresponding points, we then visualized just the splines and the two corresponding points. As the point on one spline is moved, the corresponding point on the other spline is updated. The two points should remain close and within the same cross section. Some images of the correlated points can be seen in Figure 6. Using this method, we observed that the two black points appear correlated throughout the length of the colon.

To evaluate how the system might perform in a real OC, we simulated the experience by volume rendering the correlated view from both the centerline (the view from the VC) and from the shortest path (an approximation of the view from the OC). The two views are shown side-by-side, allowing for easy comparison. Images from this simulation are shown in Figure 7. It is possible to identify structures which are present in both views, showing that the two views are properly correlated.

The simple setup would allow for easy insertion of CAD results, where the suspicious areas could be painted on the VC image but not the OC image. Such a method can help ensure that the doctor will observe the entire OC image uninterrupted, but be able to use the CAD information from the VC view.

4. CONCLUSIONS AND FUTURE WORK

This work is a first step towards a system that will fully leverage the advantages of both VC and OC in a single application. The radial undistortion of the fisheye lens allows the gastroenterologist to gain an undistorted view of the colon lumen. The correlation between centerline and hugging corner shortest path is a simple step towards trying to match information between VC and OC. By modeling the physical path of the colonoscope with the hugging corner shortest path, it is possible to approximately tell when the colonoscope is at a region that needs more thorough investigation based on the VC results.

There is much possible future work towards a VC assisted OC system. The undistortion of the colonoscope view can be useful in a system where the VC and OC images can be more fully registered. In such a system, this undistortion could allow for the color and texture information from the OC images to be overlaid on the VC images, allowing for a more realistic view. The registration method needed for this would draw heavily on computer vision techniques for matching objects. With an improved registration would come the possibility for an improved correlation between the two views. A clinical study to assess the effectiveness of the system could also be performed.

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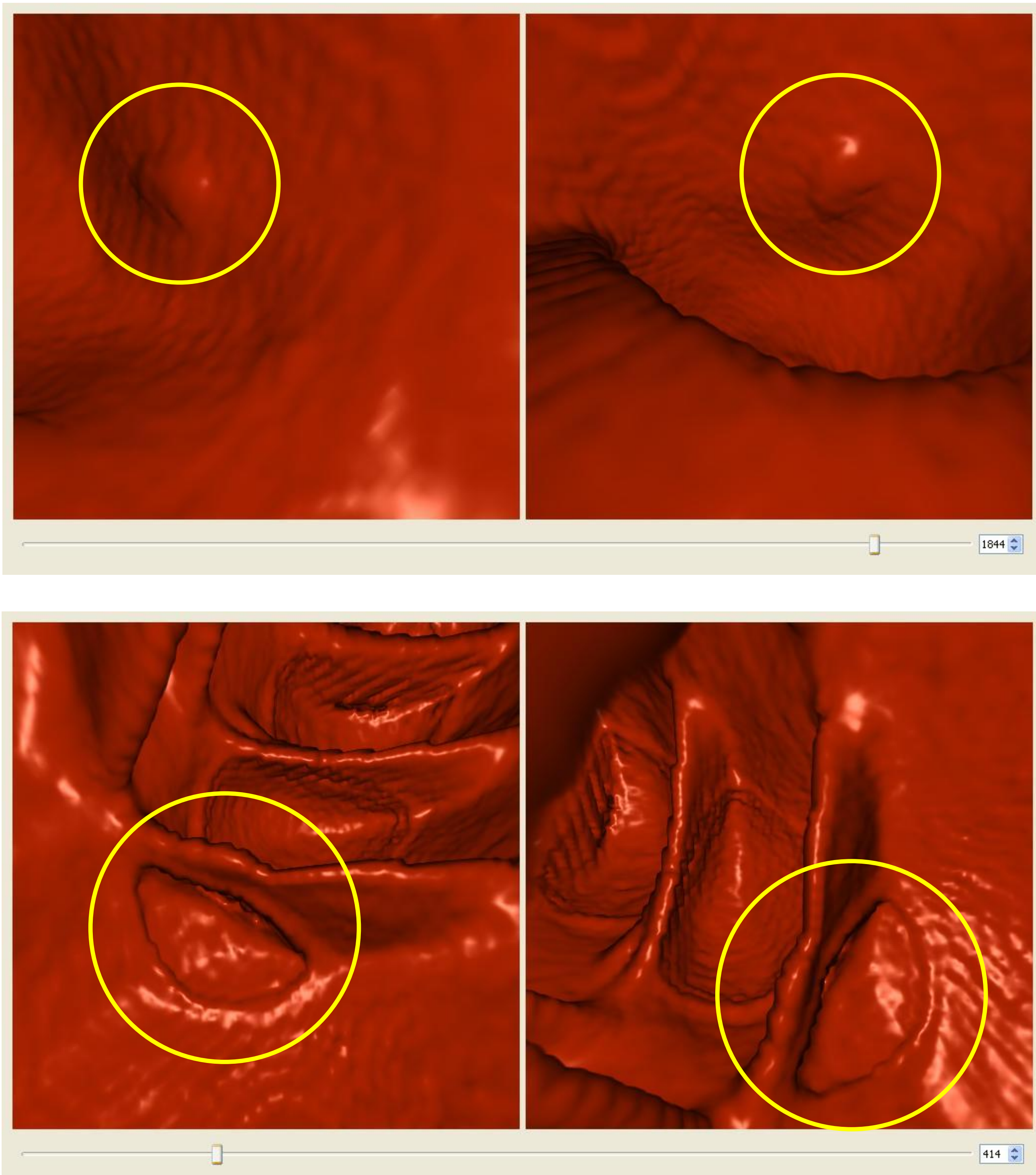

Figure 7: Screenshots of our program simulating the correlation between the two views. In both cases, the left image shows the view from the centerline, while the right image shows the view from the shortest path. Landmarks (circled in yellow) can be easily identified in both views, showing that they are properly correlated.

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