Independent Navigation System for a Surgical Colonoscope

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ABSTRACT

This paper provides a novel algorithm to attain the independent navigation of a colonoscopy surgical endoscope. First, it introduces a brief description of this issue through the scientist advance for medical robotics. It then makes a quickly count of the existent methods and at the end it provides the basis in order to propose a new alternative solution with help from vision-guidance. That means that images will be processed and interpreted with the purpose of maintaining the endoscope always at the intestine center.
All this considered will help us to reduce colonoscopy surgeries consequences and the most important advantage of this new method proposed is that surgeons will accomplish their work easier and more efficiently.

Keywords: colonoscope guidance, medical robotics, image processing and vision-based feedback.

1. INTRODUCTION

Intestine cancer is among the most frequent harmful diseases. We affirm, on the basis of statistics, that every day ten new cases of cancer colon appear. In the medicine development internal visualization of hollow organs such as intestine which has a tubular, shaped and complex geometry, has always been a very important issue of research. In addition, those techniques of internal visualization of hollow organs could be applied for visualize other organs [1].

Nowadays it exists a great deal of tests that helps to detect colorectal cancer. The first, hemoccult, is a test where we try to find blood in stool; it is the most recommended due to its low cost and to the absence of serious secondary effects; even though it has a bad sensibility and a mediocre specificity. The second, sigmoidoscopy which uses a flexible endoscope, is the examination of the large intestine from the rectum through the last part of the colon; nevertheless flexible sigmoidoscopy is not sufficient to detect polyps or cancer in the ascending or transverse colon. The last, the colonoscopy is the minimally invasive endoscopic examination of the large colon and the distal part of the small bowel with a CCD camera or a fiber optic camera on a flexible tube passed through the anus. It may provide a visual diagnosis (e.g. ulceration, polyps) and grants the opportunity for biopsy or removal of suspected lesions, it lasts 20 minutes approximately and due to the high mortality associated with colon cancer and the high effectiveness and low risks associated with colonoscopy, it is now also becoming a routine screening test for people 50 years of age or older.

Robotic surgery is the use of robots in performing surgery. Three major advances aided by surgical robots have been remote surgery, minimally invasive surgery, and unmanned surgery [1]. Major potential advantages of robotic surgery are precision and miniaturization. Further advantages are articulation beyond normal manipulation and three-dimensional magnification. Some surgical robots are autonomous, and they are not always under the control of a surgeon. They are only sometimes used as tools to extend the surgical skills of a trained surgeon. Limitations of this field are that current equipment is expensive to obtain, to maintain, and to operate for instance if one of the older model non-autonomous robots is being used, surgeons and staff need special training, furthermore data collection of procedures and their outcomes remains limited [2].

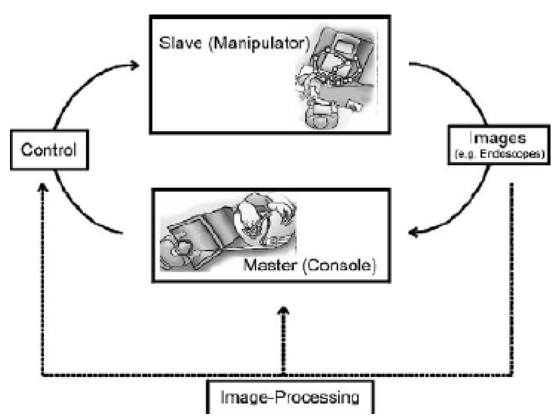

Figure 1: Diagram of a remote surgery

2. FOUNDATIONS

2.1. Colonoscopy

Above mentioned, colonoscopy is the minimally invasive endoscopic examination; its indications include gastrointestinal hemorrhages, unexplained changes in

bowel habit or suspicion of malignancy. Colonoscopies are often used to diagnose colon cancer, but are also frequently used to diagnose inflammatory bowel disease. In older patients (sometimes even younger ones) an unexplained drop in hematocrit (one sign of anemia) is an indication to do a colonoscopy, usually along with an EGD (gastroscopy), even if no obvious blood has been seen in the stool (feces).
A positive fecal occult blood test is almost always an indication to do a colonoscopy. In most cases the positive result is just due to hemorrhoids; however, it can also be due to polyps, diverticulosis, inflammatory bowel disease (Crohn's disease, ulcerative colitis), or colon cancer.

These days, two subjects of research about this issue exist [1]: real and virtual colonoscopy. The real one is based on acquired images, usually in 2D, from the intestine where structures and surfaces most be mentally reconstructed by the surgeon. In difference with the virtual one, also called "*virtual fly-through*", which uses 2D and 3D imagery reconstructed from computed tomography (CT) scans or from nuclear magnetic resonance (MR) scans, is considered like a totally non-invasive medical test, although it is not standard and is still under investigation regarding its diagnostic abilities. Furthermore, virtual colonoscopy does not allow for therapeutic maneuvers such as polyp/tumor removal or biopsy nor visualization of lesions smaller than 5mm. If a growth or polyp is detected using CT colonography, a standard colonoscopy would still need to be performed.

This procedure has a low (0.2%) risk of serious complications. The most serious complication is a tear or hole in the lining of the colon called a gastrointestinal perforation, which is life-threatening and requires immediate major surgery for repair; however, the rate of perforation is less than 1/2000 colonoscopies.

Bleeding complications may be treated immediately during the procedure by cauterization via the instrument. Delayed bleeding may also occur at the site of polyp removal up to a week after the procedure and a repeat procedure can then be performed to treat the bleeding site. Even more rarely, splenic rupture can occur after colonoscopy because of adhesions between the colon and the spleen.

As with any procedure involving anesthesia, other complications would include cardiopulmonary complications such as temporary drop in blood pressure and oxygen saturation, usually the result of overmedication and easily reversed. In rare cases, more serious cardiopulmonary events such as a heart attack, stroke, or even death may occur; these are extremely rare except in critically ill patients with multiple risk factors.

2.2. Images segmentation

Partitioning of an image into several constituent components is called segmentation [3]. Segmentation is an important part of practically any automated image recognition system, because it is at this moment that one extracts the interesting objects, for further processing such as description or recognition. Segmentation of an image is in practice the classification of each image pixel to one of the image parts.

Segmentation is a fundamental stage in this system before performing visualization, and the quality of the segmentation contributes greatly to the following colonoscopy rendering and the doctor's diagnosis.

Methods that help to extract important information for colonoscope guidance are classified into different groups: global and local ones. Difference between each one is what they are based on, that means if method adopts a region approach or a boundary approach [4]. In this research only the region approaches will be considered.

2.3. Visual servoing

Visual servoing techniques are situated in the intersection of many domains: robotics, automatics and computer vision. They use provided information from a camera in order to control movements of a dynamic system. It mainly consists of making the appropriate selection of a visual information set. After, it's necessary to map out/ draw up a law that will control the desired degrees of liberty, with the goal of that information reaches one yearned value which defines an adequate task realization. We could find three main types of visual servoing control: direct, indirect and task accomplishment [5].

2.4. Direct Visual feedback.

The vision system provides directly an estimate of the robot state and it is substituted on the low level controller of the robot.

2.5. Indirect Visual feedback.

This structure is one of the most widespread in literature; in this case, the vision system provides a set point state to the controller of robot that executes the task. This structure presents a great deal of advantages like simplicity, handheld ness and robustness because the robot is considered as an independent positioning resource of the vision system.

2.6. Accomplishment of task feedback.

3D servoing or position-based resides in the regulation of the camera situation according to his environment. The attachment between control law and measure is expressed under the form of a change of coordinates between the reference attached to the target and the one related to the camera [6].

2D servoing or image-based profits directly by analyzing/ takes directly advantage of visual information taken out from the images. The control law lies in the movement control of the camera in such a way that the error between ongoing visual information and the target wished [7].

3. METHOD

Actually, in market, there are many surgical colonoscopes that navigate in an independent way but none method is efficient enough for requirements of surgeons. For these reason we try to provide a new navigation system based on images.

The requirement to extract reliable information from images entails the use of image processing algorithms that makes slower our work. In contradiction whit that, robot movements must be controlled whit high speed. Those considerations must be realized in this research.

This development begins with the proposed algorithm, then pre-processing phase will be explained, continuing with region of interest obtaining and ending with the centre calculation.

3.1. Proposed algorithm

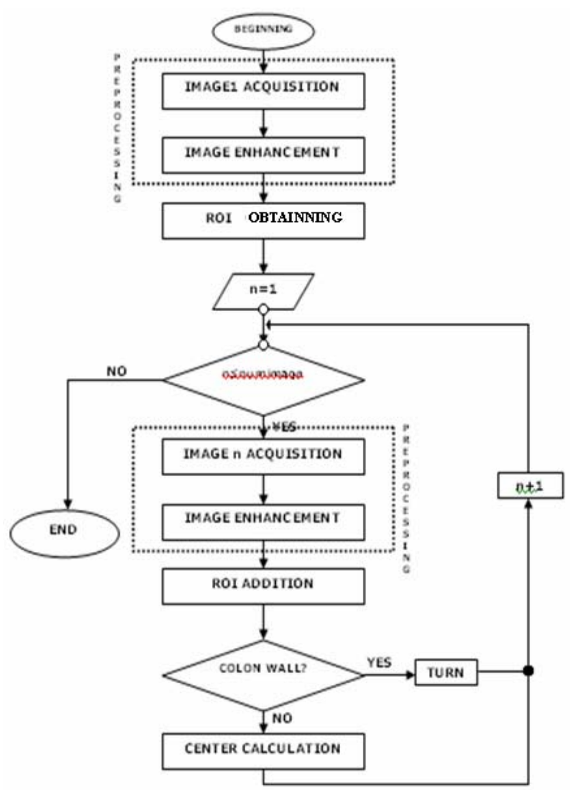

Figure 2 : Proposed algorithm

3.2. Pre-processing phase

This stage is charged of image enhancement. First images must be converted, if necessary, into a gray level. And then, we apply a median filter, a spatial filter, which estimates the median value of gray level of pixels in its window; this action is considered like smoothening. In this research, the filter use a 3*3 window, this algorithm is already in our working software.

3.3. Obtaining the region of interest (ROI)

This part is dedicated to find the action zone from acquired images. It does not exist a definitive method for this action due to the utilization of two types of images obtaining: pre-registered and real time acquired. In the first case, a threshold algorithm is used. In the second case, a seeded region-growing algorithm is applied. The region of interest is localized just once because it is treated like an object and so to place it under every new image.

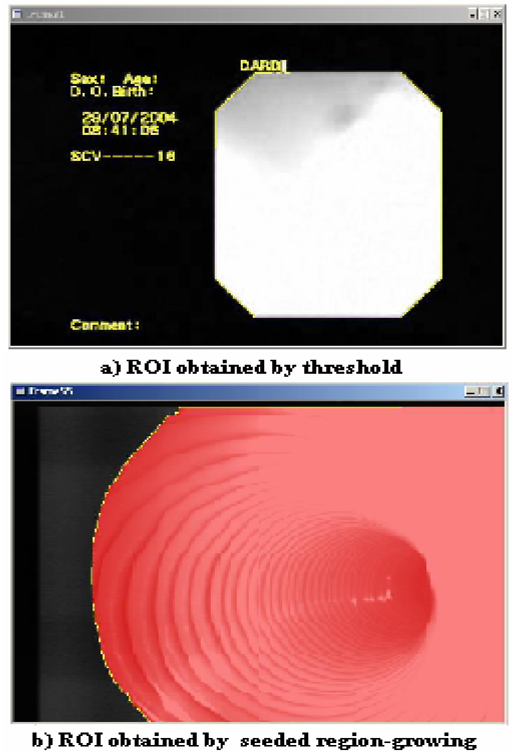

Figure 3 : Roi for a)pre-registered and b)directly acquired images

3.4. Calculation of new center coordinates

This method is already implemented in virtual colonoscopies [8] but we could take the way to find the center path and discard the rest.

In this step, we extract the surface information of a segmented object so that we can use the information in the next step of estimating the path. The surface is approximated by estimating the central axis and the corresponding cross-sectional thicknesses. The shape of a tubular object such as a human colon is well represented by the centerline of the object.

Assume that, c_i, $1 \le i \le N$ is uniformly sampled with interval on the centerline. We then define plane Π_i; it includes point c_i and its normal direction is the tangential vector of the centerline at c_i.We then assume that the object cross-section cut by Π_i approximates a circle with a radius of r_i, which represents the thickness of the object at c_i. As shown in Fig. 3(a), we then define, on the basis of the circle, a cylinder-type slice-surface S_i for c_i. S_i has a symmetric shape for plane Π_i and can be defined by the inner, centric, and outer lengths, i.e., l^{in}_i , l_{center}, and l^{out}_{i}. Note here that l_{center} is set to a constant. And we determine l^{in}_{i} and l^{out}_{i} based on the extrinsic curvature k_i at c_i. In Fig. 4(b), if $\Delta\theta_i$ is defined as

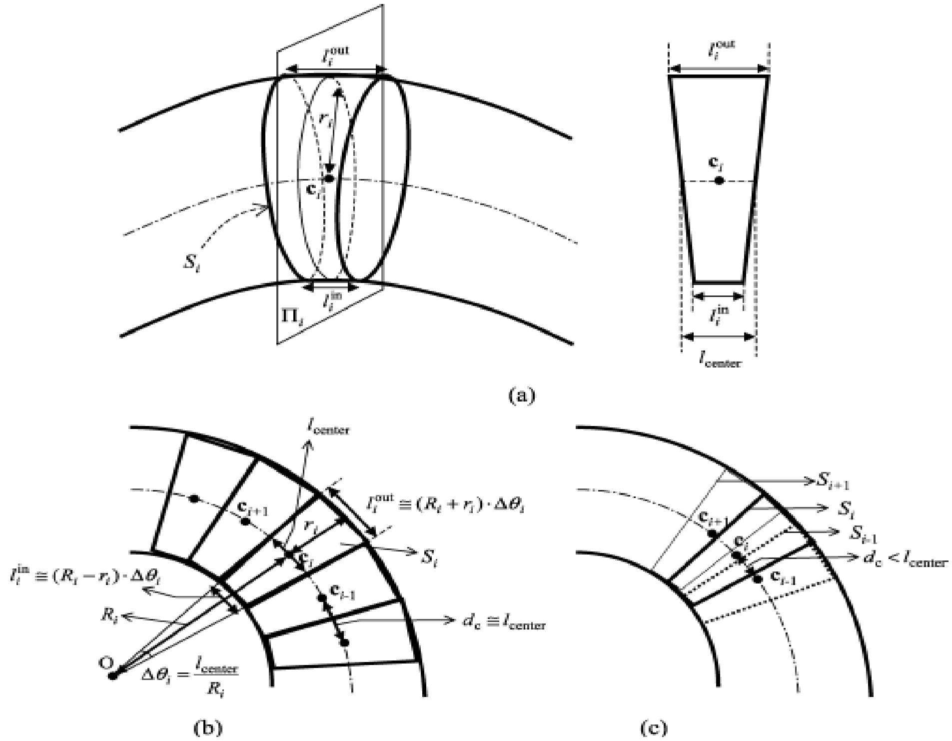

Figure 4 : Illustration of proposed algorithm

We then assume that the object cross-section cut by Π_i approximates a circle with a radius of r_i, which represents the thickness of the object at c_i. As shown in Fig. 4(a), we then define, on the basis of the circle, a cylinder-type slice-surface S_i for c_i. S_i has a symmetric shape for plane Π_i and can be defined by the inner, centric, and outer lengths, i.e., l^{in}_{i}, l_{center}, and l^{out}_{i}. Note here that l_{center} is set to a constant. And we determine l^{in}_{i} and l^{out}_{i} based on the extrinsic curvature k_i at c_i. In Fig. 4(b), if $\Delta\theta_i$ is defined as

$$\Delta\theta_i = \frac{l_{center}}{R_i} = \frac{l_{center}}{\frac{1}{|k_i|}} \qquad (1)$$

where R_i is the radius of curvature, we can obtain l^{in}_{i} and l^{out}_{i} as follows:

$$\begin{aligned} l^{in}_{i} &\cong (R_i - r_i)\Delta\theta_i \\ l^{out}_{i} &\cong (R_i - r_i)\Delta\theta_i \end{aligned} \qquad (2)$$

Then, the condition to approximate the total surface points with a minimal set of slices is

$$l_{center} = d_c \qquad (3)$$

By using (1) and (3), we can rewrite (2) as

$$\begin{aligned} l^{in}_{i} &\cong d_c(1 - r_i|k_i|) \\ l^{out}_{i} &\cong d_c(1 - r_i|k_i|) \end{aligned} \qquad (4)$$

It is interesting to note that $l^{in}_{i} = l^{out}_{i} = d_c$ for straight segments, since k_i is zero in (4). If becomes smaller than l_{center}, neighboring slices start to overlap as shown in Fig.4(c). Note here that l^{in}_{i} and l^{out}_{i} need not to be computed for path planning because they are irrelevant to the visibility. Meanwhile, the set comprising the centerline position c_i and its corresponding thickness r_i, is needed for planning path.

To obtain the centerline, we adopt an existing algorithm that is accurate, robust and not too complex [9]. By using the cross-section cut by Π_i, we may estimate the thickness r_i. But the result is sensitive to small changes in the centerline. Hence, for a robust estimation, we estimate r_i as a 3-D distance-transform value, T_i, at position c_i.

In the distance-transform procedure, we assign to each object point a Euclidean distance value between the object point and the nearest non-object point. For the 3-D distance transform, we use the chamfer-based method, which is an approximated version of the Euclidean distance transform that reduces the computational complexity. Because the distance-transform value continually varies, the thickness values that we estimate with aid of the distance transform also change continually. Hence, in some places where the thickness is abruptly changed, the estimated thickness does not accurately represent the real thickness. In the visualization, however, a smooth variation of the estimated thickness is preferred because it eventually improves the comfortableness of the navigation.

3.5. Control feedback

After images processing, 2D visual servoing is the best option for task accomplishment [10]. The purpose of this stage is to angle the surgical instrument around X and Y axis in order to bring the image projection to a specified position on the endoscopic image. The 3D point that matches with the point of instrument axis is called P. Also, the point p matches with projection of P on the image plan of the camera.

The accomplishment of task feedback seems the best option to develop this research. Visual primitives to serve are the coordinates on the image of point p. The state vector *s*, containing visual information $s_p = \{u_p \; v_p\}$, is consequently defined by coordinates on image S_p. The order is $s_p * = \{u_p * v_p *\}$, where $u_p *$ and $v_p *$ are images coordinates to reach.

The working software used (APHELION V.3.2) transmits rotation angles, in x after in y, in a tenth part so the command to transmit is

$$xAng = \frac{xDist * xAngMax}{l/2}$$

where *xDist* is the distance on x between the actual position of the camera and the position of the target on image, *xAngMax* the maximum rotation angle on x and *l* the image width.

Thus image center localized is the command transmitted to the robot which is feedback connected with the processing images computer. Thereby the robot will be able to angle needed position changes for being always placed at center of the colon and reduce then perforation risks and pains by friction.

3.6. Detecting a wall of colon

The first step of this research is estimate if image is an empty object. In order to reach this aim, obtained images are processed by threshold and a comparison is established. Thus if the object is empty, it means that colonoscope is face to a wall of colon; in this case, the colonoscope must turn 90° at left or right depending on its last position.

4. EXPERIMENTS AND RESULTS

The algorithm was completely programmed and executed in working software [APHELION] and after many test we find that it is able to:

- Define region of interest from any image.
- Detect if colonoscope is face to a wall of colon.
- Find the new coordinates of positioning.

However, for images with distortion, the algorithm was not able to detect a wall of colon. For this reason, a criterion of size and shape is introduced [10].
In addition, a wrinkled pipe, measuring 10cm of diameter, replaced the human colon; thus, the colonoscope was almost never face to a wall of colon because human colon diameter is much narrower.

Regarding visual servoing, the command was tested with an industrial robot which carries the colonoscope and the camera on its arm. Obtained results were really satisfactory because the robot changed of position and found the center of tubular colon.

Concerning time calculation, the acquisition card of the computer worked at 10Hz of frequency. The entire program is executed in 1s/image approximately. The target of proposing an efficient, robust and faster algorithm was reached. (see Fig.5)

5. CONCLUSIONS AND PERPECTIVES

In a theoretical way, this method is hard efficient concerning his robustness, time calculation and efficiency for processing images.

It provides a progress to different research fields like medical robotics, imaging, and medicine among others. Nevertheless it is just a research that needs to go into detail and to be tested with the purpose of being used in human-beings because there are still many points to enhance.

Colonoscope components enhancement is a novel issue of research, for example to hand them with a softer and more flexible material or even to give them more degrees of liberty at their top which makes easier the pass of colonoscope through the colon.

Finally, it is important to keep searching on new methods about processing images, about robustness and also about obtain a better response of surgical instruments with the purpose of facilitating surgeons' tasks.

BIBLIOGRAPHY

[1] M Gaudric. « Le dépistage du cancer du colon. La coloscopie a-t-elle une place? ». Réunion annuelle de pathologie digestive de l'hôpital Cochin - Paris - 08 février 2002

[2]W. Korb, R. Marmulla, J. Raczkowsky, J. Mu¨hling, S. Hassfeld. "Robots in the operating theatre—chances and challenges". International Association of Oral and Maxillofacial Surgeons. Published by Elsevier Ltd, 2004, pages: 721-732

[3] H. Benoit-Cattin, T. Zouagui, C. Odet. “Une vision fonctionnelle de la segmentation d'images » CREATIS, Unité de Recherche CNRS (UMR 5515), affiliée à l'INSERM.

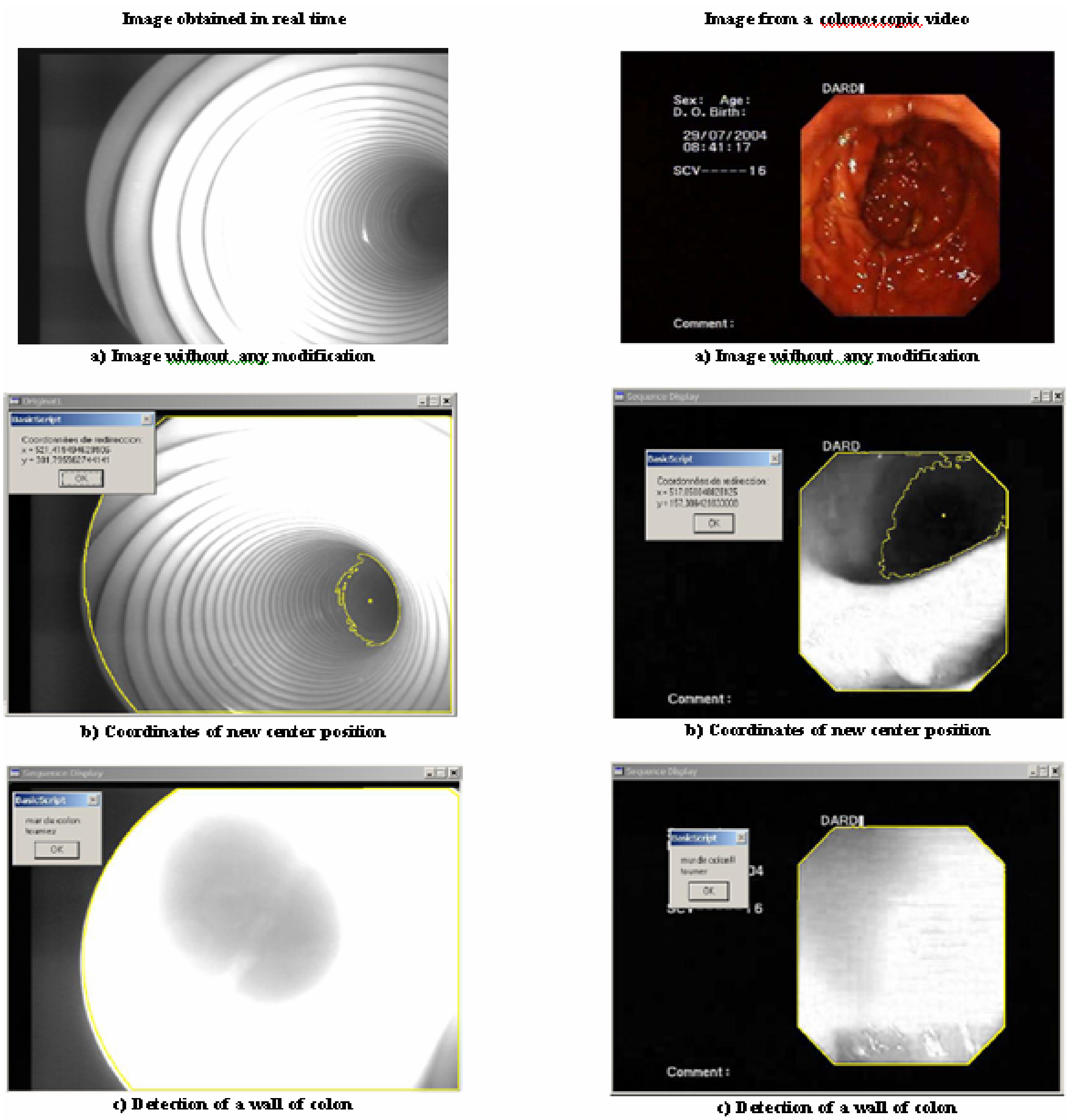

Figure 5: Results of proposed algorithm

[4] T. Zouagui. « Approche fonctionnel générique des méthodes de segmentation » PhD thèse, Institut de Sciences Appliquées de Lyon, Octobre 2004.

[5] N. OUADAH, M. HAMERLAIN et M.S. Djouadi. « Positionnement D’un Bras Manipulateur Par Une Commande Réferencée Vision »

[6] E. Malis. « Contribution à la modélisation et à la commande en asservissement visuel. » PhD thèse, Université de Rennes 1, IRISA Novembre 1998.

[7] A. Crétual. « Asservissement visuel à partir d'information de mouvement dans l'image. » PhD thesis, Université de Rennes 1, IRISA Novembre 1998.

[8] Dong-Goo Kang; Jong Beom Ra. “A New Path Planning Algorithm for Maximizing Visibility in Computed Tomography Colonography”, Medical Imaging, IEEE Transactions on, Volume 24, Issue 8, Aug. 2005 Page(s):957 - 968

[9] M. Wan, Z. Liang, Q. Ke, L. Hong, I. Bitter, and A. Kaufman, “Automatic centerline extraction for virtual colonoscopy,” *IEEE Trans. Med. Imag.*, vol. 21, no. 12, pp. 1450–1460, Dec. 2002.

[10] H. Chettahoui. « Asservissement d’une tête de coloscope dans le domaine de la robotique médicale », Mémoire M2R, Institut de Sciences Appliquées de Lyon, Juin 2005.