Endoscopic Image Processing - An Overview

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Abstract

After a brief introduction to the history of endoscopy we describe the different techniques which exist to perform endoscopic procedures (traditional endoscopy, wireless capsule endoscopy, virtual endoscopy, and confocal endomicroscopy). Then we review different medical applications and decision support systems targeted at endoscopy and summarize work in this field.

1. Introduction

The first time the term *endoscope* was used was in 1806, when Philipp Bozzini developed the first kind of endoscope which he called "Lichtleiter". By using this device he already made the first attempts to examine the inside of the human body. But endoscopes as we know them today significantly differ from the one Bozzini developed. In the early days of endoscopy the devices were lit by external light sources (a candle in the case of by Bozzini's apparatus) and not flexible. Thus they were somewhat limited in terms of their usability. Modern endoscopes are very compact devices, including a light source, a CCD or CMOS chip for taking pictures, and equipment to take tissue samples - all inside one flexible tube of a rather small diameter.

The ability to take pictures during endoscopy created a whole new field of research: endoscopic image processing. Topics in this field of research include but are not limited to image enhancement, automated decision support systems, polyp detection, and image segmentation. It is important to mention, that, while this work is focused on medical endoscopy, endoscopes are also used in other areas, such as inspection of airplanes turbines, pipes in buildings or industrial machinery, car engines, tanks in ships, and for veterinary endoscopy. The list of areas where endoscopes are used is just too long to mention them all.

In Section 2 we start with a brief historical review of the beginnings of endoscopy, followed by an overview of the technological advances in this area. In Section 3 we review various medical applications for decision support systems targeted at endoscopy and techniques used in the past throughout such systems. Section 4 concludes this review.

2 Technological advances in endoscopy

Medical endoscopy, as we know it today, is performed using an endoscope, sometimes also referred to as *videoscope*. It is made up of a CCD or CMOS chip and a flexible tube, which contains a light source at its tip. The tube also contains an additional channel, which allows the entry of medical instruments (e.g. for taking tissue samples or remove polyps). This type of endoscope has been introduced in the mid 1960s. Those endoscopes were not equipped with a digital imaging chip, but with fiber optics and an eyepiece lens. Since these days the basic concept of endoscopes did not change very much. However, modern endoscopes may be used to take digital pictures and, possibly, video sequences. Some endoscopes also offer the possibility to zoom in at interesting regions (so-called *zoom-endoscopes*). These devices offer a significant advance since smaller and finer details in the region to be examined get uncovered [7, 21]. If topical staining is applied to enhance the structural appearance of the mucosa, the procedure is referred to as *chromoscopy*. Depending on the region within the body to be examined there exist different types of endoscopic procedures such as for example *colonoscopy* for the colon, *bronchoscopy* for the airways of the respiratory system, *colposcopy* for the cervix, and *hysteroscopy* for the uterus.

But using an endoscope to inspect the inside of the human body is a rather uncomfortable procedure for a patient. Apart from that by using a traditional endoscope there are potential side effects such as perforation of organs, infection, and hemorrhage. As a consequence there has been much research to cope with these problems. Especially the small intestine is problematic since it is very long and convoluted. Therefore an endoscope can not be used to inspect the entire length of the small intestine.

One recent advance, initially developed as a better diagnosis tool for the small intestine, is the *wireless capsule endoscopy* (WCE) [2, 18]. While WCE is limited to the investigation of the gastrointestinal tract (GI tract), it has become a valuable tool, especially for detecting the cause of gastrointestinal bleeding [13, 3]. Although initially targeted at the examination of the small intestine, there are also other areas of interest for examination, for example the colon [8].

To perform WCE the patient swallows a small capsule,

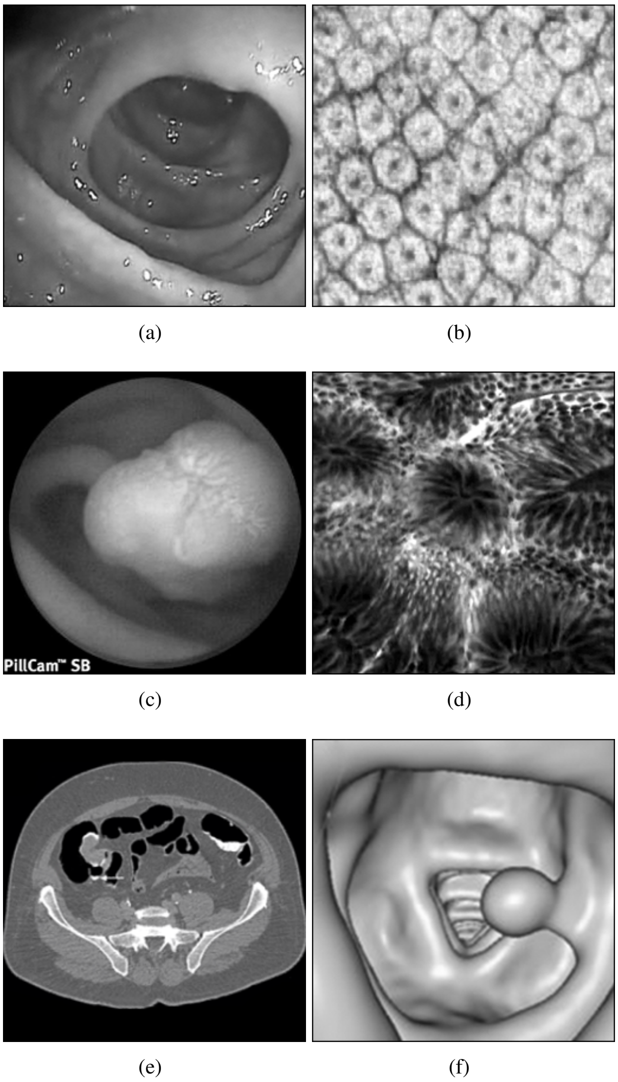

Figure 1. Images acquired by using different endoscopic techniques (a) endoscopy [9], (b) zoom-endoscopy, (c) WCE (Copyright © 2005-2009, Given Imaging. All Rights Reserved), (d) confocal endomicroscopy [10], (e) CT image slice [6], and (f) virtual endoscopy [6]

which basically contains a light source, lens, camera, radio transmitter, and batteries. The capsule then travels through the digestive system, propelled by peristalsis, and automatically takes a huge number of pictures during a traveling time of about eight hours. Since approximately two pictures per second are taken, the resulting set of images contains more than 50,000 images. These images are transmitted wirelessly to a recorder worn outside the body, hence the name. The quality of these images is still low compared to push-endoscopy (using an endoscope) and needs to be improved [15, 25].

A potential problem with WCE is an eventual retention for example in case of strictures or obstructions within the bowel, making a surgery necessary to remove the capsule. Apart from that WCE does not provide the possibility to treat lesions directly, obtain biopsy samples, clean poorly prepared areas, or influence the orientation of the camera, which are major drawbacks compared to flexible endoscopes [4].

Another recent advance in endoscopy is *virtual endoscopy* [1], sometimes also referred to as *computed endoscopy*. This method differs from endoscope-based endoscopy and WCE as it is almost completely non-invasive (apart from insufflating the bowel as a preparation step). The data to be analyzed is acquired using helical or spiral computer tomography (CT) or Magnetic Resonance Imaging (MRI scans). This usually results in a huge number of slice images, which are sometimes used directly for a decision support system. But it is also common practice to use the slices to create 3D models, which are then used for further examination by physicians. Due to the almost completely non-invasive nature of this procedure, the fact that no sedation is required, and since it is rather fast, it is a comfortable procedure for the patient.

One major drawback of virtual endoscopy is the lack of structural and color information (i.e. textural structure) since the underlying data for the 3D model basically implies positional information only. Apart from that, very small anomalies (e.g. colonic polyps) may be missed.

The most recent advance in endoscopy is *confocal endomicroscopy* [11, 16]. This procedure allows to inspect the mucosal surface in a highly detailed manner. This is achieved by a laser-based endomicroscope placed inside the tip of the endoscope which scans the surface of the mucosa. By using this technique it is even possible to inspect subsurface features up to a depth of 250 microns by adjusting the focal point of the laser. Since this method relies on fluorescent light the tissue to be examined is usually treated with fluorescent dyes.

The resulting images have a resolution corresponding to a magnification factor of 1000. As a consequence in vivo histology is getting possible and taking random and possibly unnecessary biopsies may be avoided. The field of medical applications for this new technique includes but is not limited to the detection of GI disorders such as Barrett's esophagus, gastritis, gastric cancer, coeliac disease, and colon cancer.

3 Medical applications and decision support systems

Depending on the endoscopic technique used, different medical fields exist, accompanying different sorts of reasonable decision support systems. Since each endoscopic procedure generates images which exhibit specific characteristics depending on the technique used, the computer systems targeted at decision support must be designed accordingly. Some examples for images resulting from different endoscopic methods are depicted in Figure 1.

A rough overview of common steps involved in a decision support system for medical endoscopy is shown in

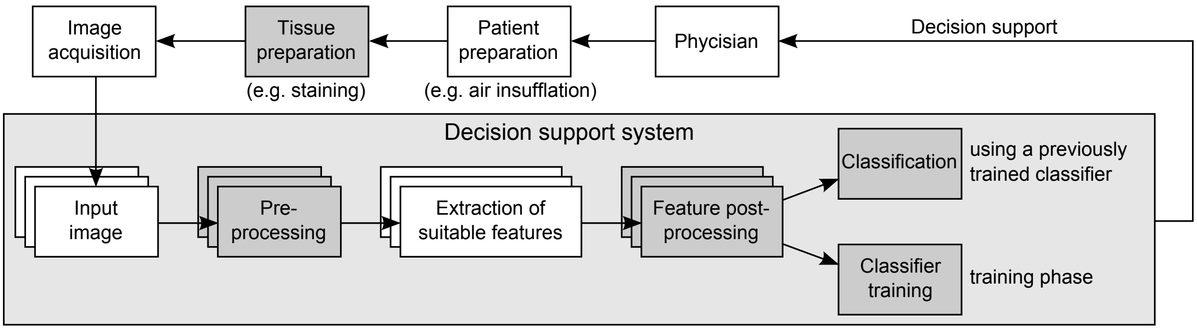

Figure 2. This figure illustrates common steps involved in a decision support system (dark gray boxes denote optional steps). Layers depict the possibility that multiple frames from an endoscopic video may be processed simultaneously to exploit inter-frame relationships.

Figure 2. In many cases the first step is a preparation of the tissue region to be investigated (e.g. staining, treatment with fluorescent dyes). After an image has been acquired, preprocessing may be required to enhance the quality of possibly degraded images. Then, depending on the aim of the application, suitable features have to be found and extracted. Sometimes a post-processing of the features is also necessary (e.g. removing invalid feature combinations in the case of high-level features). If the decision support system is targeted at classification (e.g. polyp detection, cancer detection) the features are used for a classification of the image, using a previously trained classifier. But there exist also other systems which base their decisions directly on the features without using an intermediate classifier (e.g. by using feature thresholds).

3.1 Traditional endoscopy

One area of endoscopic image processing is colon cancer detection. Although a variant of WCE (Colon Capsule Endoscopy, CCE) seems to be a promising alternative to colonoscopy [8], the methods found throughout literature are in general based on traditional endoscopes. Such systems are aimed at supporting a physician during colonoscopy, helping to identify regions within the colon which might be of interest for further investigation. Polyp detection within the colon is another area of research related to colon cancer detection, since polyps are known to be precursors to colon cancer. Successful attempts have also been made towards an automated detection of coeliac disease [28]. Other systems aim for example at detecting tumors or bleeding during bronchoscopy.

Due to the fact that images taken using a traditional endoscope often suffer from various kinds of degradations, in many cases preprocessing is applied to the imagery. One common reason for low image quality is the presence of undesired noise, which may be caused by thermal noise produced by CCD or CMOS chips contained in modern endoscopes. This is especially noticeable when images contain areas of low intensity. Methods to reduce the amount of noise within images are for example convolution with appropriate filters or low-pass filtering in the frequency domain. To overcome inhomogeneous brightness and poor contrast histogram equalization techniques are possible choices to enhance the image quality.

Another source of degraded endoscopic images is blur. Since current endoscopes do not provide the ability to focus, moving the camera at the tip of the endoscope too close to the mucosa or too far away from the mucosa may result in blurred images. Apart from that, rapid movement of the endoscope tip often results in motion blur. Especially in the case of zoom-endoscopes a rather small movement of the camera may result in noticeable motion blur. Peristalsis is also a possible source for blurred images. Possible ways to deblur images are high-pass filtering or deconvolution.

Specular highlights are also image defects characteristic of endoscopy. Caused by the light source of the endoscope, facing into the same direction as the camera, they can hardly be avoided due to the moistness of a mucosa. The detection of such highlights is not always easy, since they do not necessarily correspond to the brightest areas within an image. Therefore histogram based techniques using a global threshold tend to produce unreliable results. In the past various different methods to detect such highlights have been developed, ranging from single thresholds to multi-threshold based methods operating in more suitable color spaces (e.g. HSV), also taking into account surrounding areas of a potential reflection area.

Once specular reflections have been detected, the corresponding image areas may be masked out from further processing steps. Another possibility is to pre-classify images as out-of-focus images if the specular reflection has very blurry boundaries and is therefore not suited to extract texture features [17].

Throughout literature many different methods have been used successfully to extract features for a subsequent classification or interpretation of endoscopic imagery, with the aim of detecting possibly malignant regions. These are ranging from statistical features gathered from histograms and co-occurrence matrices, over features based on the frequency domain (e.g. by using Discrete Fourier Transform or the Discrete Wavelet Transform), to high-level features (e.g. segmentation, edge detection, or shape or ellipsoid matching against possible polyp candidates). Texture-based features are especially well suited for high-resolution techniques such as the zoom-endoscopy or confocal endomicroscopy. These methods capture textural characteristics in a highly detailed manner and are therefore able to measure texture properties from the mucosal surface which are valuable for an automated decision support.

Despite the fact that there are many possible features to be used, it has been shown by quite a lot researchers that the performance of endoscopic image classification systems can be improved by taking into account the color information available within the endoscopic imagery. This can be explained by the fact, that abnormal regions of a mucosa often also exhibit a different appearance in terms of the color (e.g. more reddish). To achieve approximate illumination invariance a common practice is to transform the images - usually stored as RGB images - to another, more suitable color space such as the HSV or the CIELAB color space prior to further investigation. The advantage of such a transform is the fact that the illumination information is contained within a separate channel which is independent of the color information. Thus a subsequent analysis may be performed on those channels only which contain the color information and vital image characteristics only.

Another branch of applications aims at helping physicians during endoscopy in terms of navigational support. Such systems are mostly targeted at colonoscopy using a traditional endoscope. The idea behind such systems is to aid the physician in advancing the endoscope through the colon, which is a fairly complex task. One common assumption in case of such systems is, that distant regions within the colon correspond to dark regions within the image taken by the endoscope. Based on this assumption various methods have been developed in the past. These works estimate the position of the lumen center from the information contained within an image (e.g. by using segmentation or histogram thresholding). Based on the output of such a system, the physician is able to align the endoscope tip properly [12, 30].

3.2 Wireless capsule endoscopy

For WCE systems targeted at navigational support, as described in the previous section, would be of no particular help since current capsule endoscopes are not steerable. However, the advent of WCE resulted in other types of image processing tasks.

One topic of particular interest is the detection of gastrointestinal bleeding (GI bleeding), which - according to the Diseases Database [1] - may be an indication for many diseases such as for example colon cancer, Crohn disease, esophageal cancer, small intestine cancer, or the typhoid fever.

[1] http://www.diseasesdatabase.com/ddb19317.htm

Due to the vast amount of images created during WCE, even experienced physicians need a fair amount of time to identify images which show abnormalities (e.g. GI bleeding). Therefore the inspection of the images by a physician is the most time consuming and therefore most expensive part of WCE [24] and the need for computer-aided decision support systems is evident.

Thus, concerning WCE, most of research done is aimed at developing reliable algorithms, which automatically detect relevant images (e.g. showing gastrointestinal bleeding) and annotate them for further analysis by a physician. The aim of these systems, also referred to as automated annotation systems, is to analyze all images taken during WCE and identify frames which contain abnormalities. This allows a physician to concentrate on relevant images only, thus saving much time. Another advantage of such systems is a more reliable detection of abnormalities which show up in one frame only, and therefore might get overseen easily by a physician. Methods to detect GI bleeding are for example based on segmentation, histogram thresholding, texture properties (e.g. local binary patterns or variants), histogram based features [14], or chromaticity moments.

Since the wireless capsule used for WCE can not be influenced in terms of traveling speed or the direction it faces, image of poor quality are very frequently the result. Therefore preprocessing steps, as outlined already in the previous section, are often necessary to cope with this problem. Apart from that, such methods also very often take advantage of other color spaces than the RGB color space.

Another possibility for the use of annotation systems is to perform a pre-segmentation of a sequence of WCE images. This is especially useful, if a physician wants to examine only parts of the GI tract. Thus such systems assign frames of a WCE procedure to the according regions within the GI tract. This allows the physician to browse through the images much faster, thus shortening the reading time of the images [2]. Related applications transform a sequence of successive WCE video frame into a two-dimensional map representing the gastrointestinal surface. This is achieved by using a model of deformable rings which estimates the motion of the capsule based on consecutive frames. The resulting map allows to quickly identify abnormalities within the WCE image sequence [26].

3.3 Confocal endomicroscopy

Due to the high-resolution of confocal endomicroscopy a very promising field is the support of in vivo histologies. But since the confocal endomicroscope generates images of a resolution at cellular level, the field-of-view is rather limited.

Therefore, one major topic of image processing research concerning confocal endomicroscopy is mosaicing, which is a procedure aiming at eliminating this limitation. For this purpose the consecutively taken images are stitched together according to the movement of the endoscope tip by an algorithm. This produces a large mosaic thus widening the field-of-view [29].

Another research topic is an automated classification based on the high-resolution images generated. By using texture features (e.g. statistical features based on co-occurrence matrices, histogram-based features, or frequency domain based features) it is possible to perform a distinction between normal and abnormal tissue [27, 20]. But also high-level features are useful for example to estimate nuclei sizes and cell density, which may help to identify pre-cancerous stages. Apart from that, scanning the complete interior of an organ is not feasible. Therefore systems specialized at detecting image regions which should be examined further with the endomicroscope may be useful.

3.4 Virtual endoscopy

For virtual endoscopy a vast amount of CT slices is generated. Inspection of these images by a physician is a tedious task. Apart from that, it is not easy to distinguish between colon walls and polyps on these images. Thus research emerging in this field is targeted at supporting physicians in detecting polyps on 2D CT slices or in 3D models generated from these slices.

Due to low radiation doses used during a CT procedure, the resulting image slices may suffer from noise. Therefore performing noise reduction is often necessary in the first place. Then, based on the fact that there exist sharp edges between air and tissue, it is possible to perform a segmentation of the insufflated volume. The segmentation result then serves as source for feature extraction (e.g. edge detection and shape matching). Other techniques are based on the normal vectors of the contours of the colonic wall gained from segmentation. By analyzing the intersections of these normals the curvature along the colon wall can be determined. This may be combined with shape matching or the Hough transform to detect circular structures [19].

Applications developed for 3D virtual endoscopy mainly consist of two kinds of necessary processing steps. The first task is to construct a 3D volume from the source CT data. This is commonly done using a region growing method (e.g. successively grow the lumen). Besides allowing a fly-through and therefore allowing a visual inspection of the virtual organ by the physician, the resulting 3D model serves as the basis for algorithms searching for polyps.

One possibility to perform this task is to create a list of possible polyp candidates based on investigating the curvature of the virtual mucosal surface. Areas protruding inwards and being round on all sides can be considered as possible polyp candidates, which can be further constrained to reduce the number false-positive candidates (e.g. by their size, sphericity, or mean curvature) [22].

Since it is important for a proposed system to be able to differentiate between polyps, folds, and colonic walls suitable features expressing specific characteristics of those entities have to be used (e.g. curvature and shape index). The curvature describes the roundness and regularity of protruded areas, whereas the shape index is a normalized value used to describe different shapes by values between one and zero. Based on these features the presence of polyps may be assessed [31].

There exists also work aimed at removing or flattening the folds of the colonic wall since these may occlude polyps. By using physics-based methods based on finite element models it is possible to stretch the surface of the colon [23]. This way the folds are flattened. The polyp candidates however remain intact without too much distortions and are therefore clearly distinguishable from the rest of the colonic wall. Another method transforms the 3D problem to a 2D problem by flattening the colon surface by using conformal mapping. This results in a 2D representation of the colon and allows pattern recognition algorithms to be applied [5].

4 Conclusion

Throughout the previous sections we gave a rough overview of currently existing methods to carry out endoscopic procedures. We have seen that, depending on the endoscopy device used, there exist different branches of research with the general goal of assisting a physician during endoscopy or analysis of the imagery acquired.

It has also been shown, that there exist tasks for which the need of computer-aided decision support systems is evident and that there is a big potential for applications with the goal of saving time or lowering the cost of endoscopic procedures. Especially when considering the fact that in the case of cancer diseases an early detection decreases the mortality rate significantly, the need for reliable computer-aided decision support and annotation systems gets even more apparent.

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