Computational vision techniques to support active capsule endoscopy

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Abstract: The present paper considers endoscopic procedures based on actively-locomoting capsules, whose movement inside the gastrointestinal tract may be controlled independently of peristalsis. Computational vision and image processing techniques are exploited, to assist both diagnostic and capsule navigation tasks, by enhancing, interpreting and displaying information acquired by the on-board micro-camera. These techniques are applied (i) towards generating a "texture map", namely a mosaic produced by stitching together the acquired images, and (ii) towards extracting visual navigation cues, in particular specifying the location of the lumen in these images.

Keywords: capsule endoscopy, active endoscopic capsules, computational vision, navigation

1. Introduction

Capsule endoscopy (CE) is based on images acquired by a micro-camera, mounted on one of the tips of a swallowable pill-sized capsule traversing the gastrointestinal (GI) tract (Fig. 1.a) (Nebeker, 2001), (Panescu, 2005). The motion of currently-available capsules is entirely due to peristalsis, which results in a significant duration of the diagnostic procedure, and prevents the explicit control the line-of-sight of the camera. On the other hand, *active* endoscopic capsules, are characterized by the controlled movement of the capsule through the GI tract, independently from peristalsis (Fig. 1.b). Various strategies for locomotion in the GI tract are currently under intense investigation by the VECTOR consortium. These include driving the capsule via an external magnetic field (Kim et al., 2005), (Uehara and Hoshina, 2003), via leg- or cilia-like lateral appendages (Menciassi et al., 2007), (Stefanini et al. 2006), (Karagozler et al., 2006), and via vibratory actuation (Zabulis et al., 2008b). Such active capsules are expected to reduce the transit time through the GI tract, as well as allow the explicit control of the camera's line-of-sight, which could be a valuable feature for diagnostic purposes.

Since vision is the main on-board sensory modality of CE systems, computational vision and image processing techniques may assist active endoscopic capsule systems in enhancing, interpreting and displaying sensory information, both for diagnostic, but also for navigation purposes. Two applications of such techniques are presented subsequently: First, the ability to summarize effectively the imaged visual content, for the purpose

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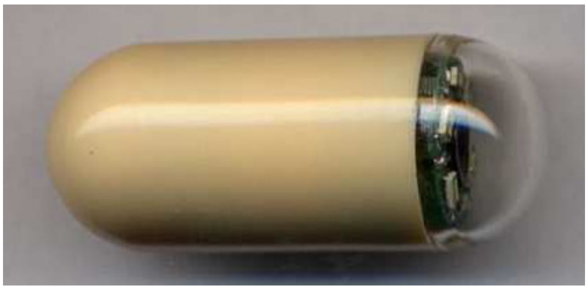
of presenting a concise overview of the GI tissue imaged during the examination. Second, the utilization of visual cues in order to partially automate the capsule navigation within the GI tract, in order to assist the capsule operator in guiding the capsule, and to allow the operator to focus more on the detailed and multi-perspective observation of regions of diagnostic interest on the tissue of the GI tract.



(a) Passive endoscopic capsule.
A micro-camera, surrounded by LEDs, is mounted at the tip of the capsule, inside the transparent dome.

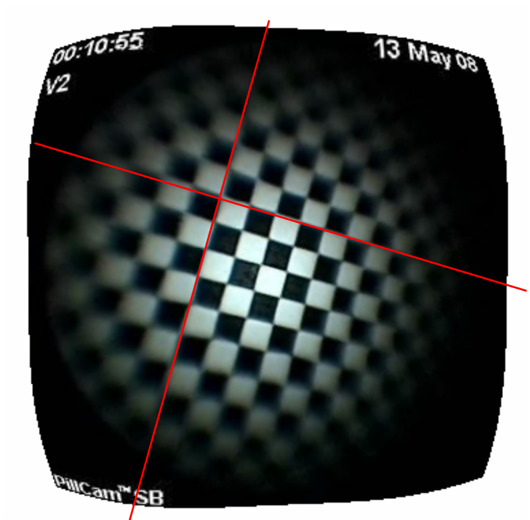
(b) Active endoscopic capsule.
In-vivo experiments with capsule driven by vibratory actuation.

Fig. 1. Prototype endoscopic capsules.

2. Texture map of the GI tissue

The role of camera calibration is considered, with respect to practical challenges in compensating for the distortions introduced by the imaging process of CE cameras (Fig. 2).

(a) Input image



(b) Corresponding undistorted image

Fig. 2: Endoscopic capsule camera calibration and image distortion compensation technique

A concise summary of GI tissue appearance, imaged during a CE examination, may be useful when comparing examinations of the same patient, acquired at different times, in order to monitor the condition of the tissue, as it develops over time. Such a summary of the visual content of the CE examination is given in the form of a "texture map", corresponding to the inner surface of the GI tract tissue. The goal is the generation of a 2D texture map that emulates an "unfolding" of this tissue onto a planar surface, for overview and inspection by the medical professional. This map should be devoid of perspective and structural distortions, and may exhibit higher resolution than the individual acquired images.

Besides the comprehensive nature of maps, which facilitates an overview of the examination, mapping of textures onto metric coordinates can be performed isotropically, allowing to make length and area measurements on this map. To generate such a texture map, image mosaicing techniques are revisited in the context of CE. Usually, such techniques assume that different images are acquired from approximately the same optical center (e.g., by only rotating the camera) or that the camera motion is known. The technical challenge in the CE arrangement is that camera motion is very difficult to estimate only from vision, due to the reduced frame rate and image resolution of these cameras, as well as lack of tissue rigidity and lack of high spatial frequency features in the image. Potential approaches are evaluated, based on preliminary results (Fig. 3).

(a) Texture map (filled left-to-right) (b) One of the input images

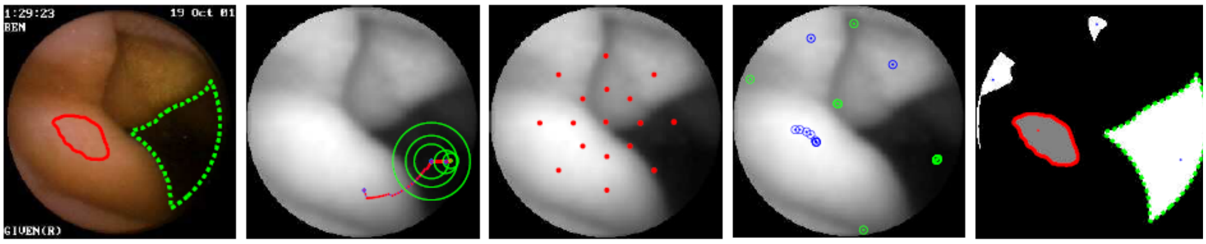
Fig. 3. Texture map of the GI tissue

3. Visual cues for active capsule navigation

Active endoscopic capsules may employ a variety of propulsion schemes to achieve controlled movement through the GI tract. However, even in the case of active capsules, the examination is still expected to last several hours; therefore, methods to automate, to the extent possible, the capsule navigation through the GI tract are being developed. This aims at relieving the capsule operator, to the extent possible, from the tedious task of continuously steering the capsule. Towards this goal, a fundamental behavior, to be implemented by the navigation system of the capsule based on visual information from the capsule camera, would be to follow the *lumen*, and, thus, avoid collisions of the capsule with the GI tract tissue.

Endoscopic capsules illuminate the GI tissue by light-emitting diodes (LEDs) mounted on the capsule in the vicinity of the camera. The illumination is not ambient and, thus, tissue closer to the light sources is imaged with greater intensity than the rest; tissue further from them is imaged with less intensity. Thus, the lumen is expected to appear darker than the rest of the tissue. When the capsule is misaligned with the GI tract, the lumen is partially seen (if at all) and the visual field is dominated by tissue close, or in direct contact, with the capsule. In this case, this tissue appears relatively brighter and the, corresponding, bright image region is referred to as the *highlight*. Therefore, two visual cues are proposed, to be exploited for the navigation of active endoscopic capsules within the GI tract, based on the detection and tracking of the lumen and of the illumination highlight in CE images.

The proposed approach aims at developing vision algorithms, which are robust with respect to the challenging imaging conditions in the GI tract and the great variability of the acquired images. A coarse-to-fine version of the Mean Shift (MS) algorithm, described in (Zabulis et al., 2008a) is employed. The main steps of the algorithm are shown in Fig. 3: Fig. 3.a shows the original image with superimposed the lumen (dashed line) and the highlight (solid line); Fig. 3.b shows the trajectory of the kernel and progressive reduction of its radius; Fig. 3.c shows the initialization seeds for multiple runs of the MS algorithm; Fig. 3.d shows the MS algorithm results for the dark (bright dots) and bright (dark dots) areas; Fig. 3.e shows the extracted regions and their boundary approximation; region representatives indicated with dots.



(a) (b) (c) (d) (e)

Fig. 4. Main steps of the lumen and highlight detection algorithm.

The detection of the lumen and highlight can provide sufficient information to reorient the camera, in order to align it with the GI tract. When the lumen is imaged, the capsule navigation system would rotate the capsule, so that the lumen is centered in the image. In cases where the lumen is only partially imaged or not at all visible, the navigation system would rotate the capsule, so that the highlight exits the image, and the entire lumen appears centered in it.

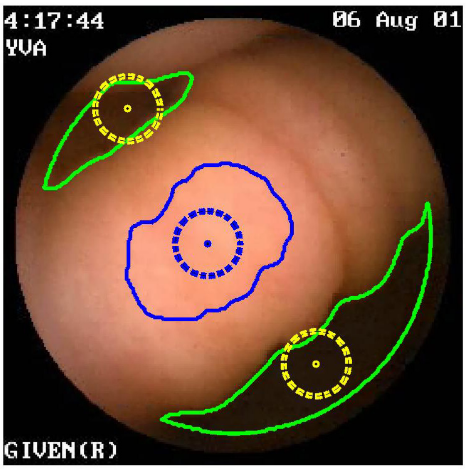


Fig. 5. Detection and tracking of multiple lumens (green contours) and highlight (blue contour), in image acquired by an endoscopic capsule

4. Conclusions

Computational vision and image processing techniques are being adapted and extended, to assist active endoscopic capsule systems in enhancing, interpreting and displaying visual information, both for diagnostic, but also for navigation purposes. Apart from the topics outlined in this paper, other related work by our group aims at developing associated computational modeling and simulation tools. These, in parallel to ex-vivo and in-vivo experiments, will enable the in-depth study of the impact that the various locomotion strategies, considered by the VECTOR consortium, may have on the imaging and diagnostic functionalities of the active CE systems (Zabulis et al., 2008a,b).

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