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Hybrid multiscale affine and elastic image registration approach towards wireless capsule endoscope localization

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ABSTRACT

Wireless capsule endoscope (WCE) enables the visualization of the interior of the gastrointestinal (GI) tract. In particular it is very important for the examination of regions in the small bowel that cannot be reached by conventional endoscopy techniques. However, when an abnormality is found in WCE images of the small bowel, it is unknown how far is this abnormality from an anatomical reference point. The primary objective of the present paper is to give a contribution to WCE localization, using image-based methods. The main focus of this work is on the description of a hybrid multiscale affine and elastic image registration approach, its experimental application on WCE videos, and comparison with a multiscale affine registration. The proposed approach intends to track the WCE motion, by using the successive WCE frames that image the walls of the elastic small intestine. It includes registrations that capture both rigid-like and non-rigid deformations, due respectively to the rigid-like WCE movement and the elastic deformation of the small intestine originated by the GI peristaltic movement. Furthermore, the proposed approach enables the extraction of two parameters (scale and rotation) from which the relative displacement and orientation of the WCE inside the GI tract can be derived, via projective geometry. Under this approach an indicator of the WCE speed can be inferred, which can be clinically useful for video interpretation. The results of the experimental tests with real WCE video frames show the good performance of the proposed approach, when elastic deformations of the small intestine are involved in successive frames, and its superiority with respect to a multiscale affine image registration, which accounts for rigid-like deformations only and discards elastic deformations.

1. Introduction

Wireless capsule endoscopy is a medical technology, noninvasive, devised for the *in vivo* and painless inspection of the interior of the GI tract. It is particularly important for the examination of the small intestine, since this organ is not easily reached by conventional endoscopic techniques. The first capsule was developed by *Given Imaging* (Yoqneam, Israel) in 2000 [1] and after its approval in Europe and the United States in 2001, it has been widely used by the medical community as a means of investigating small bowel diseases, namely GI bleeding and obscure GI bleeding (a bleeding of unknown origin that persists or recurs) [2–4]. This first capsule, for the small bowel examination, is a very small device with the size and shape of a vitamin pill. It consists of a miniaturized camera, a light source and a wireless circuit for the acquisition and transmission of signals [5]. In a WCE exam, a patient ingests the capsule, and as it moves through the GI tract, propelled by peristalsis (a contraction of the small intestine muscles that pushes the intestine content to move forward), images are transmitted to a data recorder, worn on a belt outside the body. After about 8 h, the WCE battery lifetime, the stored images, approximately 50,000 images of the inside of the GI wall, are transferred to a computer workstation for off-line viewing. Despite the important medical benefits of wireless capsule endoscopy, one main drawback of this technology is the impossibility of knowing the WCE precise location when an abnormality is detected in the WCE video. For instance, for an abnormality in the small bowel, the principal medical goal is to know how far is the abnormality from a reference point as for example, the pylorus (the opening from the stomach into the duodenum) or the ileocecal valve (the valve that separates the small

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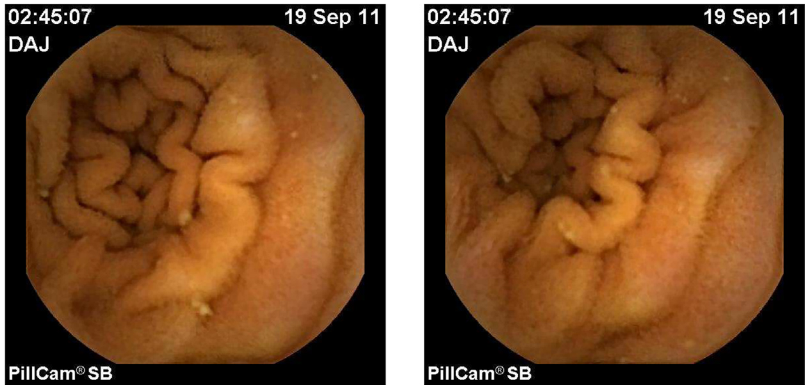

Fig. 1. Example of two consecutive frames in a WCE video.

from the large intestine), for planning a surgical intervention if necessary. Therefore, an accurate estimate of the WCE speed together with the location of one of these reference points (pylorus or ileocecal valve) would be medically extremely useful, since it would permit to measure the distance from the reference point to the capsule and consequently (*i.e.* equivalently) the distance from the reference point to the region imaged by the capsule.

Recently, there have been many efforts to develop accurate localization methods for WCE and we refer to [6] for an extended review on this topic. Generally, WCE localization techniques can be divided in three major categories: radio frequency (RF) signal based [7–12], magnetic field based [13–19], and image-based computer vision methods [7,16,17,20–28]. The first two typically require extra sensors installed outside the body.

The monitoring of the RF waves emitted by the capsule antenna is a technique that has received considerable attention in the literature. Some of the strengths of this approach are that there is no need to redesign the capsule, since each capsule has a single RF antenna, and also the potential high accuracy of the method. For instance, in [12], using a three-dimensional human body model, the authors suggest that it is possible to obtain an average localization error of 50 mm in the digestive organs. An even lower error of 45.5 mm is achieved in the small intestine. In particular, the technique presented is based on the measurement of the RF signal strength using receiving sensors placed on the surface of the human body model. In alternative, RF localization can also be based on the analysis of time-of-arrival (TOA) and direction-of-arrival (DOA) measurements [8–10]. However, a number of difficulties remain to be resolved. First, the accuracy of these methods is highly dependent on a relatively high number of external sensors. This external equipment can be very discomforting for the patient. Also, some of these techniques require the patient to be confined to a medical facility. These restrictions eliminate some of the advantages that WCE has to offer. Moreover, the real human body is an extremely complex medium having many non-homogeneous and non-isotropic parts that interfere with the RF signal. Therefore, in practise, the existing RF localization systems still suffer from high tracking errors. In addition we remark that while it is possible to use RF signal to locate the capsule in a reference coordinate system, as it goes through the small bowel, it is hard to determine the more clinically relevant information as how far has the capsule traveled from a reference point in the small bowel. This intrinsic difficulty originates from the fact that our organs move and deform in time, so knowing the coordinates of the capsule at a fixed time is not relevant clinically.

The magnetic localization technique is similar in principle to RF signal techniques. The idea is to insert a permanent magnet or a coil into the WCE and measure the resulting magnetic field with sensors placed outside the body. The permanent magnet method, unlike the coil based method, has the advantage that no external excitation current is needed. Magnetic based methods could benefit from the fact the human body has a very small influence on the magnetic field. Theoretically, the accuracy of these methods can be very high, *e.g.*, average position errors of 3.3 mm were reported in [14]. The main drawbacks associated with this technology are basically similar to those pointed out to RF methods: those are the need for a high number of external sensors and the restricted mobility of the patient. The modification of the capsule design may also be problematic. We also point out that magnetic localization systems are limited to 2D orientation estimation, since one rotation angle is missing.

One alternative technique that avoids any burden for the patient is based on computer-vision methods (*e.g.* [22,29], where the capsule localization is addressed based on image features like colors, textures and other image descriptors defined in MPEG-7 standard). Here only information extracted from WCE images is used to estimate the displacement and orientation of the capsule. Generally, these methods involve as a first step image registration procedures between consecutive video frames. The registration process is carried out through the minimization of a global similarity measure, *e.g.* mutual information [27], or the matching of local features, where algorithms like RANSAC (random sample consensus) and SIFT (scale-invariant feature transform) are the usual choices [23,25]. The following step involves the estimation of the relative displacement and rotation of the wireless capsule. Several different approaches have been proposed to achieve this goal. One such approach is to relate the rotation and scale parameters resulting from the registration scheme, with, respectively, the capsule rotation and displacement, using a projective transformation and the pinhole model [25]. Another, more complex, approach is the model of deformable rings [26]. Orientation estimation resorting to homography transformation [28] or epipolar geometry [16] has also been explored.

The main challenges in the computer image-based methods are the abrupt changes of the image content in consecutive frames and in the capsule motion, caused by the peristaltic motion and the accompanying large deformation of the small intestine. However a common simplification used in image based WCE tracking, is to neglect the non-rigid deformations of the elastic intestine walls. In this paper we develop an appropriate hybrid multiscale affine and elastic image registration strategy that tries to take into account this effect, and that overcomes the limitations of multiscale affine image registration (this latter captures only rigid-like movements in successive frames). By way of illustration Fig. 1 shows two consecutive frames in a WCE video, exhibiting elastic deformations, and demonstrating that an affine transformation composed of a planar rotation, scale and translation transformations, is not enough to match (or equivalently to register) the left with the right frame.