Endoscopic capsule line-of-sight alignment by visual servoing

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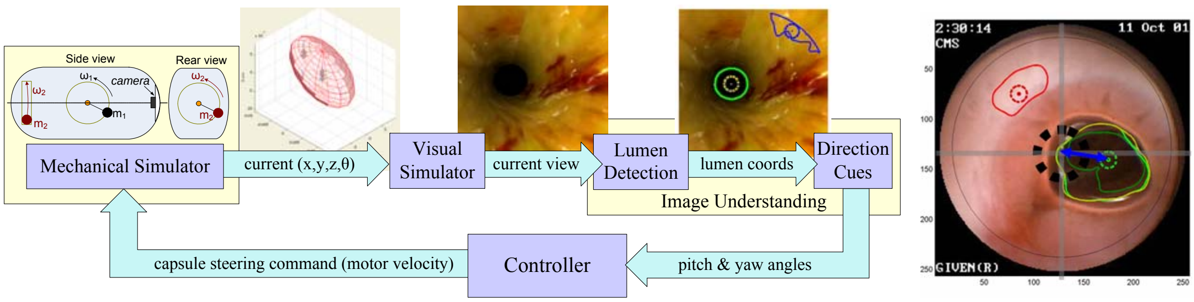
Introduction

Current research in capsule endoscopy is aimed at endowing these devices with means of active locomotion inside the gastrointestinal tract (GIT), as opposed to the present practice of passive propulsion by peristalsis. As this will entail that the physician performing the examination will also be involved in actively steering the capsule through the GIT, it is desirable that certain potentially cumbersome aspects of this task, such as traversing long segments of the intestine, are (semi-) automated. To this end, our group has been investigating the use of visual information, obtained by the real-time analysis of the images acquired from the capsule's on-board camera, for implementing appropriate such automated behaviours through *visual servoing* [1-3] techniques.
The above concepts are demonstrated here by simulations of a visual servoing scheme for navigating the capsule by aligning its line-of-sight with the GIT, as it is propelled forward, based on the detection of the intestinal lumen in the acquired images. Active locomotion of the capsule is attained by two on-board vibratory motors, generating propulsive and steering forces for planar movement.

Materials and Methods

The overall simulation framework employed to study the proposed visual servoing scheme is illustrated in Figure 1a. Details of the individual computational modules are provided next.



(a) (b)

Figure 1: (a) Overview of the visual servoing simulation framework. (b) The lumen detection algorithm applied to images acquired by a commercial endoscopic capsule.

Mechanical simulator: The mechanical simulator, which has been implemented using the SimMechanics toolbox of Matlab/Simulink, models a capsule employing twin vibratory motors in the configuration illustrated in Figure 1a. The interaction of the device with the GIT is described via a Coulomb friction model. In this setup, the system is capable of planar motion, where (in simplified terms) propulsion is adjusted via the velocity ω_1 of the rotating mass m_1, while steering is controlled via the velocity ω_2 of the rotating mass m_2. Due to the complex interaction between the forces generated by these vibratory motors, there is significant cross-coupling between propulsion and steering, which complicates motion control of the system.
Visual simulator: At regular simulated time intervals (corresponding to the frame rate of the on-board camera), the current position and orientation of the capsule are inputted to this module, which provides rendered views of the images acquired by the on-board camera, as the capsule moves inside a tube-shaped section of the GIT. The latter has been realistically textured using a high resolution image of a dissected and stretched-out strip of porcine colon tissue.
Image understanding: The images generated by the visual simulator are analyzed by an algorithm, which detects the lumen and localizes its center in the acquired image [4]. Given the camera's field of view, the orientation of the capsule relative to the "local 3D axis" of the GIT is estimated as a 3D rotation R, which aligns the capsule with this axis (Figure 1b). This rotation is defined in the capsule's coordinate frame and it can be described in terms of the *pitch angle* θ and the *yaw angle* ψ.

Visual servoing controller: The yaw angle ψ provided by the image understanding module is utilized by the motion controller of the capsule, which, for the configuration considered here, adjusts the rotational velocity ω_2 of the "steering" vibratory motor, via a PD control scheme, so as to drive ψ to zero, thus orienting the capsule toward the center of the lumen. In accordance with the characteristics of actual vibratory motors, the control signal saturates at ±12.000rpm. The rotational velocity of the "propelling" motor is held constant at ω_1=9.000rpm. It is noted that the controller utilizes only the yaw component of *R*, since the capsule is assumed to always be in contact with the GIT tissue.

Results

Indicative simulation results, demonstrating the efficacy of the proposed visual servoing scheme for aligning the line-of-sight of the capsule with the center of the detected lumen, are shown in Figure 2.

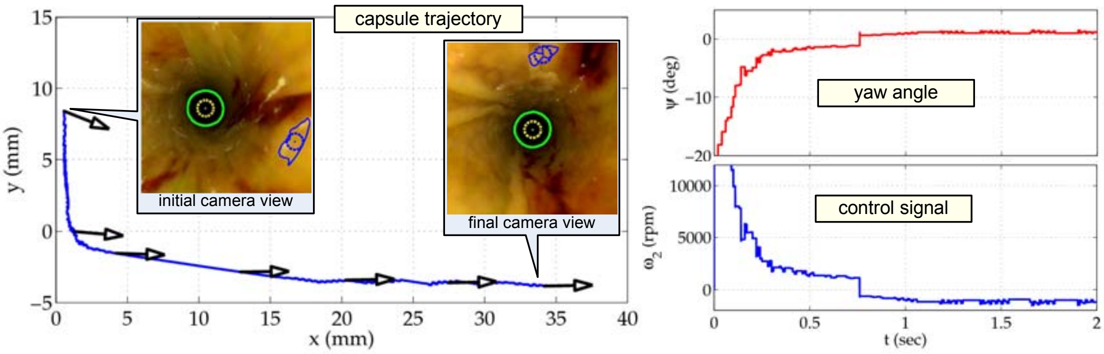


Figure 2: Simulation results for the visual servoing scheme based on lumen-detection.

Discussion

A number of refinements are currently pursued for the presented scheme, including the development of more sophisticated control strategies and of more realistic models for the capsule's interaction with the GIT tissue. Furthermore, in other scenarios, the rotation *R* can be computed based on the detection of other visual features, such as the center of a region-of-interest, in order to steer the capsule towards the corresponding tissue regions to facilitate the acquisition of images from diagnostically significant vantage viewpoints.

Preliminary work towards the practical implementation of the presented scheme has included: (i) experimental investigations and simulations verifying that the capsule vibrations do not cause significant degradation to the quality of the images acquired by the on-board camera [5], (ii) the assessment of the lumen detection algorithm on data from related in-vivo experiments [4], and (iii) the development of various vibratory-actuated prototypes. It is also noted that the proposed scheme can be adapted to work with alternative methods of active capsule locomotion, e.g., by means of an external magnet mounted on a robotic arm. A series of test-beds are also under development for the experimental evaluation of this concept.

Acknowledgements

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