30th Annual International IEEE EMBS Conference
Vancouver, British Columbia, Canada, August 20-24, 2008

Effects of vibratory actuation on endoscopic capsule vision

Xenophon Zabulis, Michael Sfakiotakis and Dimitris P. Tsakiris

Abstract— **Current research in capsule endoscopy aims at endowing the capsules with some means of actively propelling themselves inside the gastrointestinal (GI) tract, as opposed to the present practice of passive propulsion by peristalsis. Advantages of these active capsules are the significant potential reductions in the duration of the associated diagnostic procedures, as well as the possibility to direct the line-of-sight of the on-board cameras towards interesting features of the GI tissue. One such means of active propulsion is by vibratory actuation, employing eccentric-mass micromotors, which is shown to reduce the friction of the capsule with the GI tract. The effect of vibrations on the quality of the acquired images is explored in the present study, which demonstrates that such vibrations do not affect adversely the diagnostic effectiveness of the endoscopic capsules. The parameters of vibratory actuation are evaluated as to the loss of high-frequency information in the acquired images, due to the induced motion blur, and appropriate design guidelines for the vibratory actuation system are established. The validity of this study has been evaluated by ex-vivo and in-vivo experiments.**

I. INTRODUCTION

Capsule endoscopy (CE) [1], [2] is a diagnostic procedure, in which a swallowable pill-sized capsule is utilized to acquire images through the gastrointestinal (GI) tract, employing a microcamera mounted on one (or both) of its tips. This is a lengthy procedure (typically lasting from 6 to 18 hours), since the capsule moves passively through the GI tract by means of the naturally-occurring peristalsis. Recent research efforts have focused on methods for actively controlling the capsule's motion, in order to reduce the duration of the procedure, as well as to increase its diagnostic value (e.g., by directing the camera's line-of-sight to specific regions of interest) [3], [4].

In contrast to conventional endoscopes, where wiring through the probe facilitates high-resolution imaging and high frame rate, in CE the wireless transmission of images and power-consumption constraints impose limited frame rate and image resolution. As an example, the widely used endoscopic capsule *PillCam* developed by *Given Imaging* [5], delivers images of 256 × 256 pixels at a frame rate of 2 Hz. Therefore, it is crucial that any active-locomotion principle to be used in CE gracefully integrates with the image acquisition process and does not result to a significant degradation in the quality of the acquired images.

In this context, the present paper focuses on the effect of vibratory actuation schemes, currently under investigation for CE, on imaging quality. The main effect of concern is motion blur, due to the vibration-induced capsule motions while an image is being acquired. The parameters of vibratory motion are studied in relationship with the quality of the acquired images, in terms of clarity and - therefore - diagnostic value. The motivation is to facilitate the initial design of an appropriate system and to provide insights regarding the integration of vibratory actuation with image acquisition in CE.

In Section II of the paper, the proposed vibratory actuation motion principle is presented and demonstrated experimentally. A series of computational tools, the development of which is described in Section III, are then employed in Section IV for a parametric study, where the simulated capsule trajectories are utilized to predict and to evaluate the quality of images acquired in the presence of vibrations. Associated experimental results, involving in-vivo tests of prototype capsules integrating vibratory actuation and imaging modules, are provided in Section V.

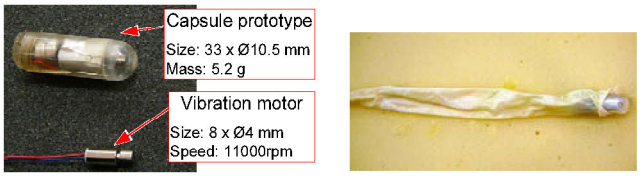
II. VIBRATORY ACTUATION

Our group is currently investigating vibratory actuation schemes for capsular endoscopy, employed either as a stand-alone locomotion method or in conjunction with other means of capsule propulsion. For the latter case, in particular, we are interested in the use of vibrations for reducing the frictional resistance encountered by the endoscopic capsule when moving through the GI tract. A number of previous studies have analyzed theoretically and demonstrated experimentally this frictional reduction through vibrations for the sliding contact between metals (see, e.g., [6], [7]), as well as for medical devices which exploit this principle [8], [9].

A series of prototype devices, integrating on-board eccentric-mass motors, has been developed, in order to investigate vibratory actuation schemes for endoscopic capsules. The prototype shown in Fig. 1a employs a rod-shaped vibration motor, whose axis of rotation is aligned with the capsule's main axis, and which is powered by a pair of watch batteries. Using a custom test-stand, based on a motorized linear stage and a high-precision force gauge (*Alluris FMI-210A5*), the frictional resistance of this prototype was evaluated, as it was being pulled through flexible tubular environments simulating the GIT, for both activated and non-activated vibrations of the on-board eccentric motor, at different traction velocities. Indicative force data from experiments with the capsule moving through a collapsible latex tube (see Fig. 1b), which was lined with liquid soap (simulating the presence of mucus), are shown in Fig. 2. The obtained results, for three different traction

This work was supported in part by the European Commission, through the IST project VECTOR (FP6-033970). The authors are with the Institute of Computer Science, Foundation for Research & Technology - Hellas, N. Plastira 100, Vassilika Vouton, GR-700 13, Heraklion, Crete, Greece. {zabulis,sfakios,tsakiris}@ics.forth.gr

velocities (3, 6 and 9 mm/s), confirmed the reduction of friction through vibrations for the developed prototypes. This appears to become more pronounced as the traction velocity is reduced and indicates that vibratory actuation schemes may provide for smoother and potentially more precise positioning of endoscopic capsules in the GIT. This calls for further investigation of the effects that these vibrations may have on the functionality of the endoscopic capsule, primarily with respect to imaging. To this end, appropriate computational tools, as well as prototype devices, have been developed; these, along with associated simulation results and experimental observations are presented in the following sections.



(a) (b)

Fig. 1. (a) Preliminary capsule prototype with vibratory actuation. (b) The latex tube GIT simulator.

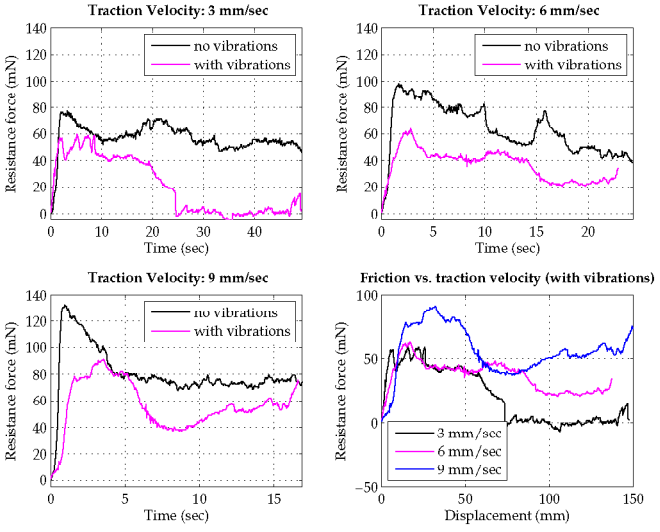


Fig. 2. Frictional force measurements for the vibratory capsule prototype moving inside the latex tube.

III. COMPUTATIONAL TOOLS

This section provides an outline of the main computational modules, developed by our group for studying propulsion- and vision-related aspects of endoscopic capsules. The general software architecture integrates two main modules, namely (i) the mechanical model of the capsule and its interaction with the environment, whose implementation is based on the SimMechanics toolbox of Matlab/Simulink, and (ii) an environment sensing module, incorporating a simulator of the capsule's vision system, which is developed in C++ enhanced with the DirectX graphics libraries. Bidirectional data exchange between these two modules allows for setting up simulations of sensor-based closed-loop control schemes. The configuration of these modules, with respect to the specific requirements of the present study, is presented next.

A. Mechanical Simulator

The mechanical model of the vibratory capsule configuration under consideration is illustrated in Fig. 3. Inside the capsule of mass M, there is a smaller mass m, which describes a circular trajectory of radius r, as it rotates at constant angular speed ω on the plane vertical to the capsule's main axis, about point O. Compression-wise viscoelasticity of the biological tissue is modelled through a Voigt spring-and-damper element, characterized by an elastic stiffness coefficient k and a damping coefficient b. The frictional force F_R resisting motion of the capsule is described by a combined Coulomb and viscous force model whose parameters (stiction level and viscosity coefficient) are functions of the normal force F_N applied by the system to the substrate (F_N presents periodic variations, brought about by the rotation of the mass m).

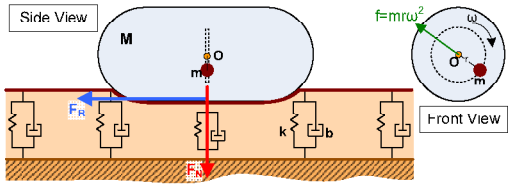


Fig. 3. Mechanical model of the vibratory capsule.

B. Visual Simulator

A simulator of the image acquisition process was developed where the performance of vision systems within the GI tract may be evaluated, under a variety of locomotion and motion control strategies. This simulator utilizes a cylindrical textured 3D model of the GI tract and a virtual camera. The scene is illuminated by a virtual light source, which is located behind the camera, and is of equivalent flux to the combination of the LEDs on the capsule. Given the location of the image center and the orientation of the optical axis, as inputted from the mechanical simulator, an image is synthesized. In order to provide realistic renderings of the visual appearance of the GI tract, a high-resolution image of freshly-dissected and stretched-out porcine colon tissue was obtained, and subsequently used to texture the cylindrical model in the visual simulator (Fig. 4).

The simulation of images under vibratory motion is implemented as follows. The trajectory of the capsule, given the parameters of vibratory actuation and a discretization of

Fig. 4. Original photograph utilized in texture acquisition for the simulator.

time $t_d = t_{int}/N$, is simulated for the camera integration (or exposure) time t_{int}, where N is a constant that determines the temporal-discretization granularity of this simulation process. The capsule trajectory is inputted to the visual simulator, which positions the virtual camera through all the simulated locations of the trajectory and at the corresponding orientations. At each location of the trajectory, an image is synthesized. The synthesized images throughout the trajectory are pointwisely averaged to simulate the acquisition of the image, during t_{int}. In essence, N is the number of synthesized images. To realistically simulate the acquisition process, a large value of N minimizes discretization error below pixel accuracy.

IV. SIMULATION STUDY

The mechanical model is employed to generate the different vibratory trajectories of the system, when the parameters of the rotational-mass actuator, which generates these vibrations, are varied in a systematic way. For each parameter set, the resulting trajectory is subsequently fed into the visual simulator to define a 3D path of the system moving inside the virtual intestine. Having appropriately specified the relevant parameters of the imaging system (namely the integration time of the sensor and its output resolution), the visual simulator provides an image, corresponding to the output of the camera for the prescribed motion of the capsule during the time interval of image integration.

The acquisition of an image under vibratory motion imposes motion blur that may reduce the sharpness and value of the acquired image as a diagnostic modality. The purpose of the simulation is to predict the effects of different values of the vibratory motion parameters on image quality and facilitate the comparative assessment of the different vibratory actuation configurations, under investigation. To quantify the sharpness of the acquired image, its frequency domain is considered. Since image detail is represented by high image frequencies, the shift of the image frequency components towards lower frequencies, due to motion blur, is observed. To represent this shift, the histogram of image frequency components with respect to the amplitude of the corresponding components is utilized, as follows.

For each frequency component of the image, a value $v_i = f_i \cdot a_i$ is computed, where f_i is the frequency of the i^{th} component and a_i its amplitude. For a given image, the values v_i are collected and their histogram is formed. The median μ of this histogram is selected as a *sharpness metric* and is a representative of the frequency distribution in the image. The metric quantifies the effect of motion blur on the whole image spectrum (high and low frequencies). It aims at indicating the frequency shift due to image blur, not at being an absolute quantification of this blur. It is noted that the energy of the high-frequency 2D Daubechies wavelet component [10] has been also considered, yielding findings similar to those obtained with the μ metric.

The basic parameters of the mechanical model of the system have been configured to reflect those of our prototype, while, in the visual simulator, the camera integration time

TABLE I

INDEX NUMBERS OF SIMULATION RUNS

Baseline conditions:	1, 2, 3		
	$\omega_0/2$	ω_0	$\omega_0 \times 2$
m_0 / 2	4, 5, 6	7, 8, 9	10, 11, 12
m_0	13, 14, 15	16, 17, 18	19, 20 21
$m_0 \times 2$	22, 23, 24	25, 26, 27	28, 29, 30

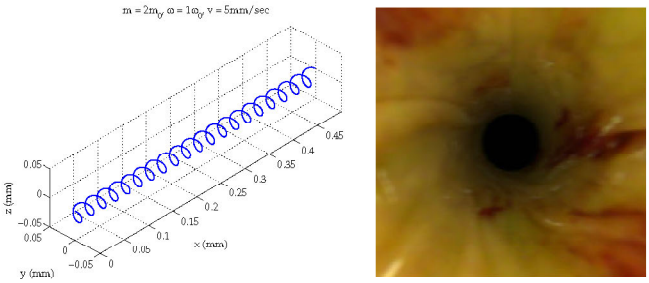


Fig. 5. Sample results of the simulation studies: (a) Vibratory trajectory of the system. (b) Corresponding output of the visual simulator.

was specified as $t_{int} = 0.1$ s (a typical value for a CMOS camera), and the temporal discretization parameter was set to $N = 10^3$. The parametric study was then performed by running a series of simulations, to obtain the vibratory movement characteristics of the system, by considering for the rotating-mass actuator (i) three different values of the rotating mass m, namely $m = m_o/2$, $m = m_o$ and $m = 2m_o$, where the nominal mass m_o of the eccentric motor used is $m_o = 0.02$ g, and (ii) three different values of the rotational velocity ω, namely $\omega = \omega_o/2$, $\omega = \omega_o$ and $\omega = 2\omega_o$, where ω_o is the nominal rotational speed of the eccentric motor (12000 rpm). For each parameter combination, trajectories were obtained for three different average velocities of the system, namely for $v = 2$, 5 and 10 mm / s. To provide a baseline for the assessment of the acquired images, three additional trajectories were also considered, corresponding to the vibration-free movement of the system, for each one of these three velocities. The different experimental conditions were enumerated as shown in Table 1. Each combination of ω with m is sequentially numbered for the three evaluated velocities. For example, simulation runs 4, 5 and 6 correspond to $m = m_0/2$, $\omega = \omega_0/2$, and velocities 2, 5, and 10 mm/s, respectively. Simulation runs 1, 2 and 3 are the baseline conditions for the velocities of 2, 5, and 10 mm/s, respectively. Indicative results are shown in Fig. 5.

In Fig. 6, the results of the comparative evaluation are summarized by plotting the values of the sharpness metric μ; the lower the value, the heavier the blur. The horizontal axis maps the index number of the evaluated simulation run, as enumerated in Table 1. In general, the capsule vibrations do not appear to significantly degrade the quality of the acquired images, for the range of the parameters tested. More specifically, image sharpness is mostly affected by the eccentric rotating mass m, and demonstrates comparatively

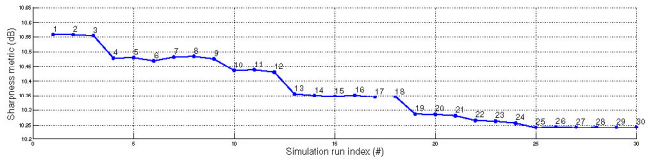


Fig. 6. Simulation results: the sharpness metric, evaluated for the different parameter combinations of the mechanical model.

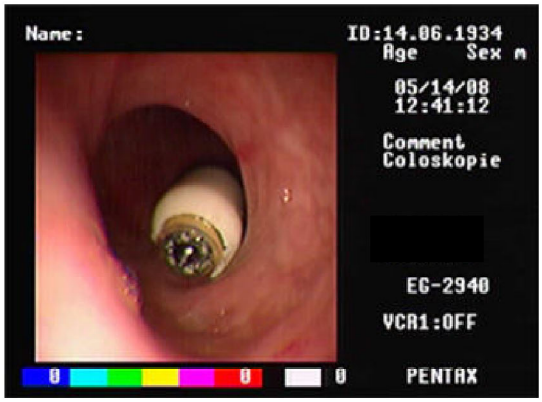


Fig. 7. In-vivo experiments with the integrated vibratory capsule prototype.

little variance as either the frequency of the vibrations or the mean velocity are increased.

V. IN-VIVO EXPERIMENTS

In order to experimentally assess the effect of vibratory actuation on the imaging quality of endoscopic capsules, a series of vibratory prototypes with on-board imaging have been developed and evaluated through both ex-vivo and in-vivo testing. One such prototype, shown in Fig. 7, integrates a commercial endoscopic imaging system (PillCam capsule by Given Imaging) with a coin-shaped vibratory motor (nominal motor speed: 12000rpm at 3 V), whose axis of rotation is aligned with the capsule's main axis.

During in-vivo experiments of this capsule prototype moving inside the GI tract of a pig, images were acquired by the on-board camera, both with and without vibratory actuation. The main finding of the comparative assessment of these images is that, in consistency with the predictions of the simulations, vibratory actuation appears to have very little (if any) effect on the imaging quality. Practically no significant motion blur is exhibited, and fine tissue texture (e.g. veins) is retained, indicating that the diagnostic value of the images is not degraded. In addition, images under vibratory actuation do not exhibit any compelling feature that would allow their discrimination from the images acquired without vibrations. Fig. 8 presents examples from both datasets, demonstrating these findings for images of similar anatomical structures.

VI. CONCLUSIONS

The present study has demonstrated, both via simulations and experimentally, that the motion parameters of vibratory actuation schemes (in the range specified by the mechanical

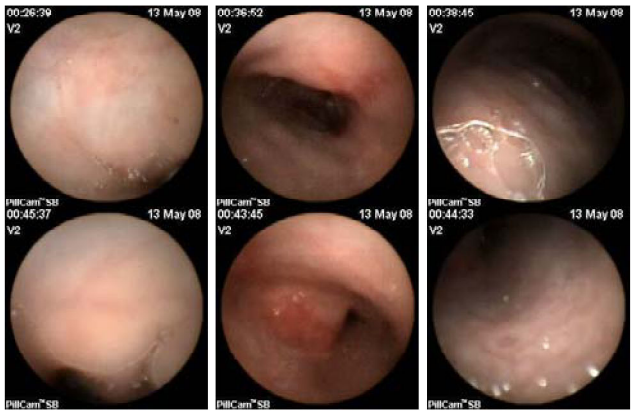


Fig. 8. Comparison of images acquired with (top row) and without (bottom row) vibratory actuation. Images of similar (but not the same) anatomical structures are shown.

capabilities of the investigated systems) do not result in significant degradation of the image quality. In particular, minimal additive vibration-induced motion blur was observed. The simulations indicated that, for the studied range of velocities, minimizing the eccentric rotating mass m is the most important guideline. However, this represents a design tradeoff, since reducing the friction by the generated vibrations depends, in part, on increasing m. Future work will further investigate the effect of vibratory actuation on standard image processing tasks, such as edge detection and feature extraction.

VII. ACKNOWLEDGMENTS

The authors thank N. Pateromichelakis, N. Kyriazis and the members of the VECTOR consortium for their technical assistance.

REFERENCES

[1] F. Nebeker, "Golden accomplishments in biomedical engineering," *IEEE Eng. in Medicine and Biology Mag.*, vol. 21, pp. 17–47, 2001.
[2] D. Panescu, "An imaging pill for gastrointestinal endoscopy," *IEEE Eng. in Medicine and Biology Mag.*, vol. 24, no. 4, pp. 12–14, 2005.
[3] I. Kassim, L. Phee, W. S. Ng, F. Gong, P. Dario, and C. A. Mosse, "Locomotion techniques for robotic colonoscopy," *IEEE Eng. in Medicine and Biology Mag.*, vol. 25, no. 3, pp. 49–56, 2006.
[4] A. Menciassi, M. Quirini, and P. Dario, "Microrobotics for future gastrointestinal endoscopy," *Minimally Invasive Therapy*, vol. 16, no. 2, pp. 91–100, 2007.
[5] G. Iddan, G. Meron, A. Glukhovsky, and P. Swain, "Wireless capsule endoscopy," *Nature*, vol. 405, p. 417, 2000.
[6] C. C. Tsai and C. H. Tseng, "The effect of friction reduction in the presence of in-plane vibrations," *Archive of Applied Mechanics*, vol. 75, no. 2, pp. 164–176, 2006.
[7] W. Littmann, H. Storck, and J. Wallaschek, "Sliding friction in the presence of ultrasonic oscillations: superposition of longitudinal oscillations," *Archive of Appl. Mechanics*, vol. 71, no. 8, pp. 549–554, 2001.
[8] K. Yoshinaka, K. Takashima, T. Okazaki, K. Ikeuchi, T. Washio, and K. Chinzei, "Experimental study to control the insertion resistance of internal medical instrument using magnetic field oscillation," *Tribology International*, vol. 40, pp. 339–344, 2007.
[9] T. Shin-Ei, K. Yuyama, M. Ujihira, and K. Mabuchi, "Reduction of insertion force of medical devices into biological tissues by vibration," *Japanese Journal of Medical Electronics and Biological Engineering*, vol. 39, no. 4, pp. 292–296, 2001.
[10] I. Daubechies, *Ten lectures on wavelets*. SIAM, 1994.