Sensors and Actuators A 186 (2012) 270–276

Contents lists available at SciVerse ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

A wireless module for vibratory motor control and inertial sensing in capsule endoscopy

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ARTICLE INFO

Article history:
Available online 20 December 2011

Keywords:
Capsule endoscopy
Medical micro-robotics
Vibratory actuation
Magnetic active locomotion

ABSTRACT

The development of active locomotion approaches for endoscopic capsules – as opposed to the passive traversal of the gastrointestinal (GI) tract by natural peristalsis, which is the current clinical practice – is expected to significantly enhance the diagnostic and therapeutic functionalities of these devices. Exploitation of external magnetic fields as locomotion strategy currently represents the most promising approach for the active guidance of endoscopic capsules. In addition, the use of capsule vibrations is currently under investigation, in order to further enhance the maneuverability of the capsule by reducing its friction with the GI tissues. Towards this end, we present here the development of a capsule prototype, which integrates permanent magnets with a vibrating motor and a triaxial accelerometer, along with an electronic module allowing remote control of the motor and wireless transmission of the inertial data to a host PC. *Ex vivo* tests confirm both the efficacy of vibrations for reducing friction, as well as the adequacy of the inertial sensing scheme in capturing the characteristics of the capsule vibrations. It is expected that these findings could be exploited for the on-the-fly adjustment of the vibratory motor frequency, based on the accelerometer data, in order to adaptively minimize the capsule friction during the entire endoscopic procedure.

1. Introduction

Wireless Capsule Endoscopy (WCE) has the potential to dramatically reduce invasiveness and pain of traditional gastrointestinal (GI) diagnostic procedures, paving the way to mass screening of the GI tract [1]. From this perspective, WCE is an example of "disruptive" technology, one that induces a radical change in the way humans operate. It potentially enables inspection of the GI tract without discomfort or need for sedation and thus reduces considerably the risks associated with traditional endoscopy [2]. As a first-generation disruptive technology, WCE still presents a number of limitations, *e.g.*, the inability to control locomotion and camera orientation. As demonstrated by recent comparative studies [3] these open issues allow traditional endoscopic techniques to still be superior to WCE. Therefore, the evolution of WCE should consist in integrating mechanisms for active locomotion and providing capsules with micro-sensors and micro-tools for diagnosis, therapy and minimally invasive surgery (MIS) [4–7]; this can be done taking always in consideration that one of the main constraints in the integration of robotic features and advanced diagnostic tools is the limited onboard power.

Several research groups and companies are pursuing this approach exploiting advances in mechatronics to enhance the WCE capabilities, transforming these capsules from simple diagnostic cameras to complete and autonomous diagnostic and therapeutic robotic platforms [8,9]. Different approaches have been proposed for providing active locomotion capabilities to the WCE capsules but, currently, the most feasible solution appears to be magnetic steering. A promising approach, that takes advantage of active magnetic locomotion in the GI tract combined with an accurate driving of the capsule by a robotic arm, was developed in [10]. Although this was demonstrated to be a reliable solution to move and steer a capsule in a slightly insufflated intestine in *ex vivo* and *in vivo* conditions, it forces the capsule to move in contact with the intestinal wall, exerting significant contact forces. Moreover, the capsule demonstrated jerky movement at times, even loss of the magnetic link, especially in movements through collapsed segments of the GI tract. The reduction of the frictional forces may therefore enhance the maneuverability of the device and reduce the risk of tissue damage during the examination. A friction reduction mechanism would

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doi:10.1016/j.sna.2011.12.024

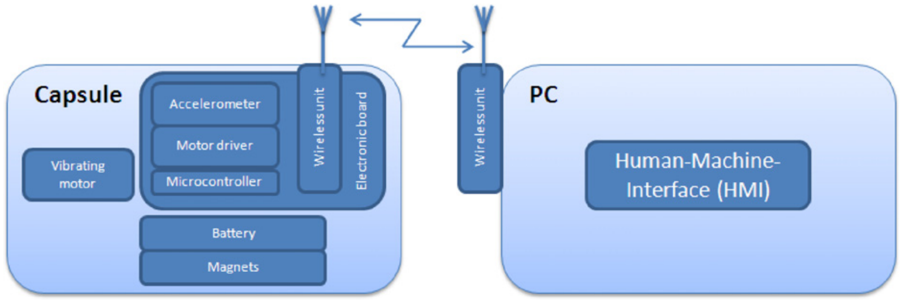

Fig. 1. System architecture of the overall system.

then be a valuable component of such devices. For this purpose, capsule vibrations have been proposed by some of the authors and were shown to be a simple and effective such mechanism, which does not affect adversely the capsule's imaging process [11]. Early qualitative *ex vivo* and *in vivo* tests of endoscopic capsules provided with vibratory actuators indicated that, despite of the slight increase in the weight of the devices, their movement in the presence of vibrations became smoother and better controlled. These observations prompted the systematic exploration of this concept by appropriate capsule prototypes, dedicated experimental facilities, and a series of *ex vivo* and *in vivo* tests.

Along these lines, the present study considers a capsule prototype developed and evaluated experimentally, which integrates a coin-shaped vibrating motor, an onboard battery, permanent magnets, a custom electronics module for remote acquisition and control, and a triaxial accelerometer aimed both at reducing the friction between capsule and substrate by means of vibration, as well as sensing the vibrations' characteristics.

The prototype has been evaluated using a dedicated *ex vivo* test-bench and a Human-Machine Interface (HMI), aimed at studying the reduction of the frictional forces needed to manipulate the capsule, as well as the accuracy of the inertial sensing of the vibrations. These results could be employed towards the implementation of automated strategies for the automated adjustment of the rotational velocity of the vibrating motor, based on data from the accelerometer, in order to adaptively maximize the effect of frictional reduction during traversal of the GI tract. Moreover, the proposed diagnostic devices could, then, be exploited in a magnetic guidance-based active locomotion platform, like the one developed and presented by the authors in [10].

This article is organized as follows: Section 2 provides an overview of the hardware and software design of the prototype, Section 3 describes the accelerometer characterization using an external displacement sensor, and Section 4 presents the experimental investigations on friction reduction using vibrations. Finally, Section 5 discusses the obtained results and outlines relevant future work.

2. Materials and methods

2.1. System overview

A miniaturized capsule-shaped prototype has been developed. The mechanical system comprises the capsule-shaped protective shell, which encases a vibrating motor, an electronic board, a battery, permanent magnets and three electrical magnetic contacts. The electronic system consists of a miniaturized ZigBee compliant round-shaped wireless electronic board, that includes a motor driver for a brushless and direct current (DC) motor, as well as a triaxial digital inertial sensor to detect acceleration with high data rate.

On the software implementation level, specific event-driven finite-state-machine codes were developed and implemented in a pseudokernel-based system, in order to receive data from the inertial sensor and control the brushed motor pulse with a high-performing time scheduling and without dropping wireless data messages during time critical tasks. A high-level software control station HMI was developed and implemented on a Personal Computer (PC) for the sensor-based control of the capsule. A general overview of the system architecture is presented in Fig. 1, while a detailed description of the individual modules of the system is provided in the next sections.

2.2. Mechanical system design

A miniaturized capsule-shaped prototype with a diameter of 15 mm, a length of 34 mm and a weight of 8.2 g was developed (Fig. 2). A main component of the capsule is the coin-shaped shaftless vibrating motor (310-101, Precision Microdrives Ltd., UK) with a diameter of 10 mm, a thickness of 3.4 mm and a weight of 1.2 g, which generates centripetal forces by means of an eccentric rotating mass. The mass is rotated with an angular frequency of up to 150 Hz (controlled by the electronic board), determining the vibrations with discrete levels of frequency and amplitude. In order to increase the amplitude of the vibrations, the motor is placed in the front side of the capsule at the maximum distance from the capsule's centre of mass.

A set of permanent magnets (3 rows of axially magnetized NdFeB magnets with a remanence of 1.48 T – K&J Magnetics, Inc., USA) has been included in the capsule, allowing its manipulation by the operator using external magnetic field sources [10]. The magnets have been placed on the external side of the capsule, in order to amplify the magnetic link with the external magnet, while the system's battery (Plantraco, USA, 3.7 V, 30 mA h, 1.2 g) was placed between the electronics board and the magnets. The electronic board integrates a digital triaxial accelerometer, which is used to measure the capsule vibrations' amplitude and frequency. In order to acquire properly the vibrations, special attention has been given to place the board in the capsule geometric centre in a stable configuration. The protective shell is fabricated using a 3D printer machine (Dimension Elite, Stratasys Inc., USA) from ABS plastic, a material widely used in biomedical research and sufficient to obtain long-lasting watertight sealing. The two half-shells were glued together using common epoxy glue, to waterproof the prototype for use in wet *ex vivo* and *in vivo* experimental conditions. Three magnetic contacts in the rear of the capsule provide access to the battery (for power supply charging and voltage measuring) and for re-starting and waking up the microcontroller.

2.3. Electronic system design

A custom-made wireless miniaturized control board, based on the 8051 family embedded microcontroller and provided with

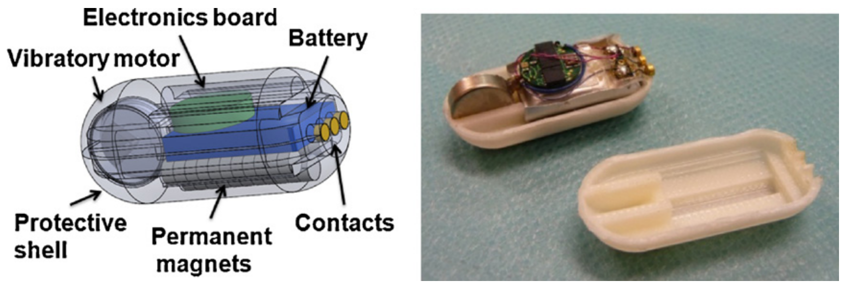

Fig. 2. Computer aided design (on the left) and assembly of the vibrating capsule (on the right).

a wireless communication module was developed by integrating state of the art off-the-shelf components, in order to control the brushed DC motor and to record data from an accelerometer sensor (Fig. 3a). The electronics board exploits the CC2430 (Texas Instruments, USA) System-on-Chip (SoC) core component, selected for the wireless controllability over 2.4 GHz ZigBee compliant radio hardware and the suitable dimension to be deployed inside the capsular device (Fig. 3b) [12]. The board design and specifications were critically investigated due to the dimension constraints; a circular shape was selected to optimally conform to a cylinder-shaped endoscopic capsule. The four-layer electronic board prototype, including the IEEE 802.15.4 compliant transceiver, is 9.6 mm in diameter and has an overall thickness of about 2.5 mm [13].

A dual H-bridge A3901 motor driver (Allegro Microsystems Inc., USA) was installed on the electronics board for the control of the vibrating motor. A digital triaxial accelerometer (LIS331DL, STMicroelectronics Inc., Switzerland) was positioned in the centre of the round-shaped electronic board, in order to record acceleration data from the capsule with maximum output data rate of 400 Hz. The sensor was interfaced to the microcontroller in a master/slave manner, exploiting a synchronous serial data link standard (Serial Peripheral Interface Bus, SPI) that operates in full duplex mode. In order to properly interface the wireless electronic board to the HMI, a second CC2430-based module was exploited and connected to the PC with a Universal Serial Bus (USB) port, through an off-the-shell USB/serial Universal Asynchronous Receiver-Transmitter (UART) converter development module for the FT232R IC device (UM232R, Future Technology Devices International Ltd., UK) (Fig. 3c).

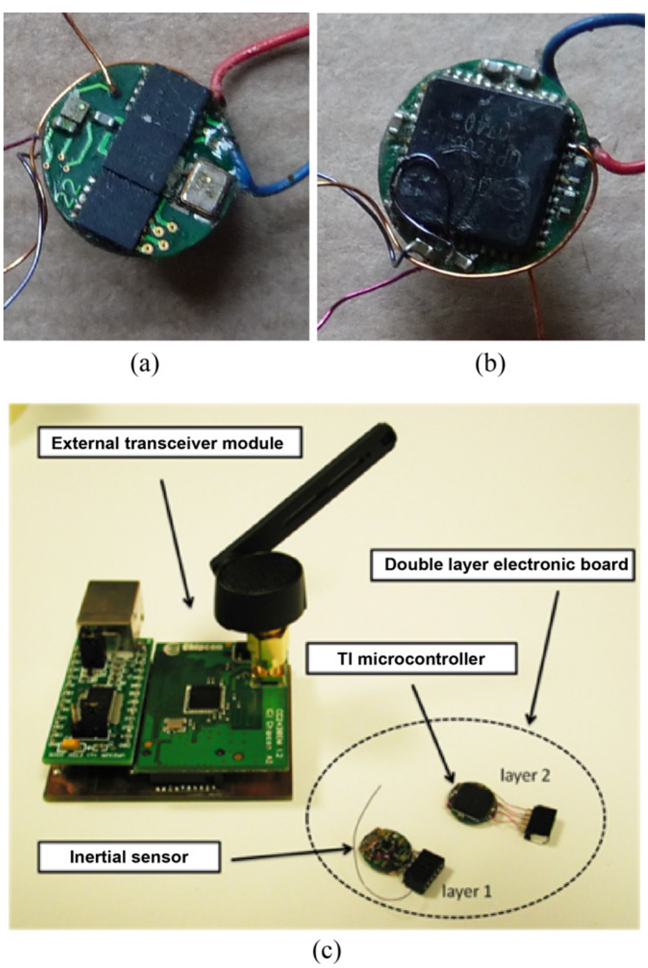

Fig. 3. Custom-made wireless miniaturized electronic board for the control of the brushed DC motor and for recording data for an inertial sensor. (a) Accelerometer and motor driver board layer, (b) microcontroller board layer, and (c) the external transceiver/receiver together with the capsule's electronic board (on the right) are depicted.

2.4. Software implementation

The installed peripherals (*i.e.*, accelerometer sensor and DC brushed actuator) have very strict time deadlines, therefore a *real-time* embedded software implementation must be developed to handle time critical tasks during the data acquisition and control process; a customized pseudokernel approach was exploited, as reported and described in detail in [13]. The pseudokernel system, developed in C++ programming language on the IAR Embedded Workbench development platform (IAR Systems, Sweden), consists of an event-driven finite-state-machine code, coroutine, and a pooled-loop algorithm able to send up to 139 bytes of data within an average response time of 20 ms and wireless communication of 52 kb/s.

A robust state-driven code task for the accelerometer was implemented by the authors with the aim to accomplish high output data rate in order to efficiently detect capsule vibration amplitude and frequency. The proposed approach consists in recording a set of acceleration data in a volatile buffer array with a defined time scheduling to be sent each communication cycle in two's-complement arithmetic. In the same cycle, while the previous buffer array is sent, a new acceleration packet is recorded and is prepared to be sent at the next communication cycle. Based on the buffer size and the proposed sensorial hardware specification, eight single-axis acceleration values, or two sets of triaxial acceleration values are continuously stored in the buffer array to be received each communication cycle by the HMI. Therefore, thanks to the several accelerometer information sent each wireless average communication time of 20 ms, a higher accelerometer sampling frequency, 400 and 100 Hz for single-axis and triaxial sensor data respectively, can be achieved.

In the proposed application, a brushed DC motor has to be activated and controlled wirelessly in order to adapt the vibrations frequency and amplitude values of the capsule. A reliable state-driven

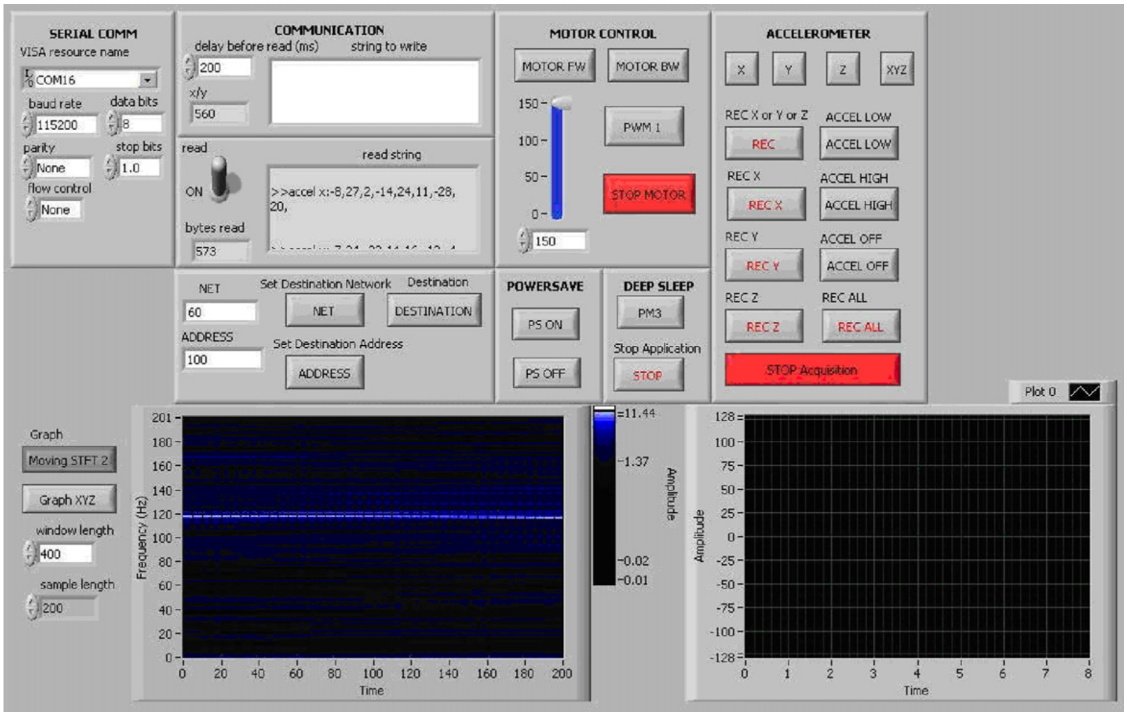

Fig. 4. Human–Machine–Interface (HMI).

code task was implemented with the aim to simultaneously control frequency and direction of rotation of the motor, and was integrated in the pseudokernel overall operating system. The software control task manages the motor operation by a digital Pulse-Width Modulation (PWM) control method, which is wirelessly controlled imposing a variable duty cycle parameter by the HMI.

The external transceiver/receiver communication module implements a second pseudokernel based software application and acts as a communication bridge between the capsule device and the PC for data management and message processing.

The higher-level HMI was developed in LabVIEW (National Instruments, USA) as a control panel to receive sensory feedback from the capsule, and send control commands to the connected peripherals. In particular, the HMI can be employed by the user to select the serial communication options, the motor control commands, *i.e.*, frequency and direction of rotation, and several accelerometer options, *i.e.*, measurement axes, acquisition rate, and maximum acceleration measurement range. At the same time, a *real-time* fast Fourier transform (FFT) module provides visualization of the capsule vibrations' frequency and amplitude. The HMI can also be used to select power management modes for the microcontroller, to reduce the current consumption. A screenshot of the developed HMI is provided in Fig. 4.

3. Accelerometer characterization

In order to validate the accelerometer output, a measurement procedure using an external high-precision laser interferometer (optoNCDT1402, Micro-Epsilon, Germany: sampling frequency 1.5 kHz, accuracy 1 μm), exploited as displacement sensor, has been performed. The capsule is placed over a bundle of six strips of opened small intestine tissues, exactly underneath the laser sensor beam. The capsule was powered by an external supply, to maintain a constant reference voltage of 3.6 V on the electronic board, and the motor was powered with fractions of the reference voltage, using PWM. When the motor vibrates at the selected frequency, the capsule vibrations are recorded simultaneously by the accelerometer and by the displacement sensor. The motor velocity is varied from zero to its maximum value using six discrete PWM steps. The procedure has been repeated multiple times for each motor frequency, every time renewing the top-layer strip of intestinal tissue. The embedded accelerometer acquires data during these experiments, with a frequency of 400 Hz along the *Z*-axis, and with a measurement range of ± 4 g. The averaged results, obtained after appropriate processing of the acquired data, are summarized in Fig. 5a and b.

The frequency, shown in Fig. 5a, is computed with FFT analysis of both the displacement and the acceleration sensor data. The amplitude of the vibrations (Fig. 5b) is measured directly by the displacement sensor, while double integration has been used for the estimates obtained by the corresponding accelerometer data. A correlation between the accelerometer and displacement sensor data is observed, verifying that the developed prototype can provide reliable estimations for the frequency and amplitude of the capsule actual vibrations (average errors of 2.7 ± 1.7 Hz and 20.3 ± 13.8 μm respectively). An additional series of measurements has been performed under dynamic conditions, where the capsule is placed on six layers of open intestine and it is dragged with a linear constant speed, obtaining similar results.

Moreover, it was observed that the gyroscopic forces produced by the rotating mass along with the low centre of gravity are keeping the capsule orientation planar (vibration motor always remains vertical), so the accelerations are measured always on the right direction. Additional measurements have been performed to investigate possible interference of the permanent magnetic field on the motor performance, without observing any kind of interferences.

4. Experimental investigations: *ex vivo* test on small and large bowel

4.1. Test bench

Experiments measuring the frictional force of the integrated vibratory capsule inside porcine intestinal tissue were performed,

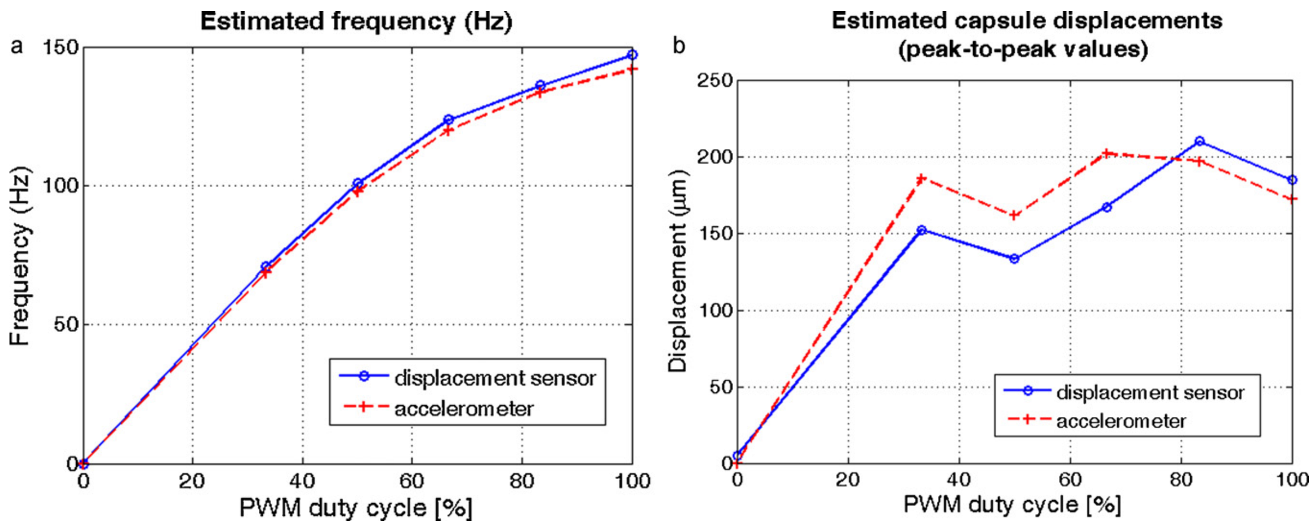

Fig. 5. (a) The vibrations frequency [Hz] and (b) displacement [μm] estimated by the external distance sensor and the embedded accelerometer simultaneously.

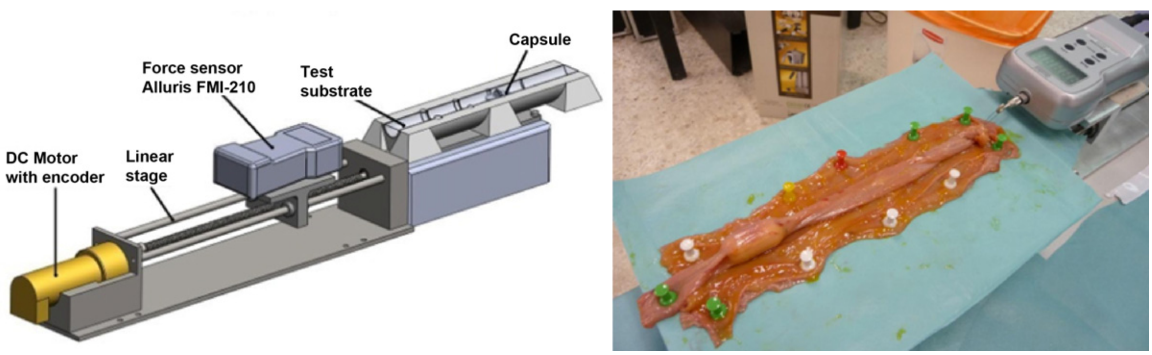

Fig. 6. Illustration of the employed experimental test-bench (on the left) and a picture of the *ex vivo* scenario during the measurements (on the right).

in order to study the effect of the rotational velocity of the vibratory motor and relate capsule vibration frequency to frictional reduction. Rather than employing magnetic steering, these tests were performed by pulling the capsule through the tissue with a motorized linear stage, since such a setup facilitates the reproducibility of the experiment and, consequently, increases the reliability. To this end, a dedicated *ex vivo* test-bench has been used, shown in Fig. 6, which consists of a linear stage and a digital force sensor (FMI220, Alluris GmbH, Germany: sampling frequency 1 kHz, accuracy 1 mN). The linear stage employs linear rods and ball bearings to restrict movement of the object to a single axis of motion. A DC motor with encoder and variable acceleration/deceleration phases is rotating a worm screw, which translates the platform with controllable velocities of up to 6.7 mm/s, with a 220 mm overall stroke. The force sensor is mounted on the movable platform in a horizontal orientation. The prototype is placed on the substrate of choice (*i.e.*, samples of *ex vivo* intestinal tissue), and is pulled at a constant linear speed of 6 mm/s *via* a thin, non-deformable surgical string attached to the force sensor. The motion profile of the linear stage and the rotational velocity of the vibrating motor inside the capsule are controlled by a host PC, while the measurements from the force sensor and the onboard accelerometer are acquired through serial RS232 interfaces, displayed on the user interface presented in Fig. 4, and stored for post-processing.

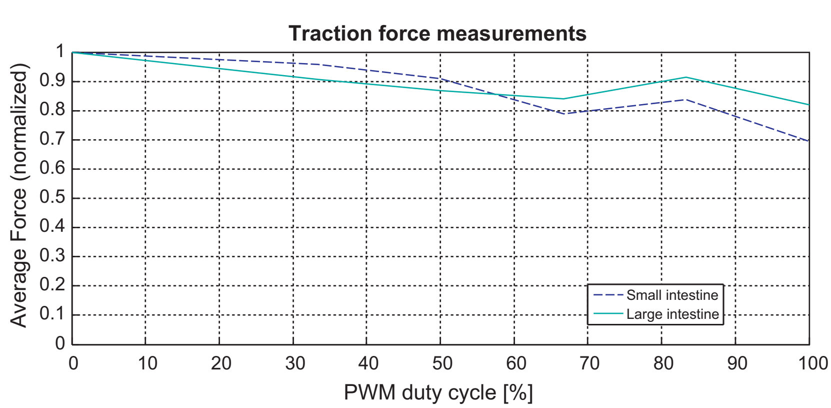

Fig. 7. Reduction of the frictional forces as the vibration motor frequency increases, for movement of the capsule through small and large collapsed intestinal tissue.

4.2. Results

Using the dedicated *ex vivo* test-bench, the capsule has been tested in two environments, namely in collapsed segments of porcine small and large intestinal tissue, in order to study the effect of frictional reduction in the capsule's movement at different rotational velocities of the onboard vibration motor. For both environments, the experiment was performed 10 times for each one of 5 different PWM settings, in order to reduce statistical errors in the computing of the average frictional force. As can be seen in Fig. 7, results indicate a reduction of the frictional forces by 31% for the small, and by 18% for large intestine tissues at the maximum rotational velocity of the vibrating motor (obtained for a 100% PWM duty cycle), which corresponds to a frequency of 150 Hz. For movement through collapsed small intestine, the average force values were found to be 0.281 N for no vibrations *versus* 0.194 N for the case of maximum vibrations; for movement through the large intestine samples, the corresponding forces were 0.824 N and 0.676 N, respectively.

Considerable friction reduction of 22% for the small and 16% for the large intestine (forces of 0.221 N and 0.693 N respectively) has been observed for a PWM duty cycle of 66%, which corresponds to a frequency of 125 Hz measured by the accelerometer. These results suggest that sufficient force reduction may still be obtained when a lower vibration frequency is used, demanding less energy from the battery. Since the onboard battery can only provide a limited amount of power, which yields about 25 min at 100%, 45 min at 66% and over an hour at 50% of motor actuation, running the motor at lower frequencies could be important for a simple screening procedure which is possible within an hour using an endoscopic capsule guided by external magnetic field. For invasive and therapeutic procedures, like biopsy sampling and drug release, where longer operation times would be required, an inductive powering system has been developed and successfully tested with the vibrating motor [14].

5. Conclusions and future work

We have presented a miniaturized capsule-shaped prototype, which integrates a coin-shaped vibrating motor and an onboard inertial sensor, towards the study of employing vibrations to reduce friction between an endoscopic capsule and the GI tract. Initially, using an external displacement sensor, we were able to verify that the embedded accelerometer can provide reliable estimations for the frequency and amplitude of the capsule vibrations. Preliminary *ex vivo* tests were then performed, using a dedicated test-bench, to evaluate the friction of the prototype as a function of the vibration motor speed. The results indicate a reduction in frictional forces of up to 31%, suggesting that capsule vibrations can enhance the maneuverability of endoscopic capsules, as well as reduce the risk of tissue damage during its movement through the GI tract. Considerable reduction in frictional forces has also been observed at a lower vibration frequency, allowing for a longer battery life, in line with the requirements of a complete endoscopic procedure.

Future work will involve the development of computational models, as well as further experiments with the test-bench presented here, in order to comprehensively study the effect on frictional reduction of the characteristics of the vibrations, the overall mass of the capsule, and the properties of the locomotion substrate. It is expected that such studies will provide useful guidelines towards the development of appropriate schemes for the automatic tuning of the capsule vibrations, in order to adaptively optimize the frictional reduction effect during traversal of different parts of the GI tract. Additional *ex vivo*, as well as *in vivo* experiments will also be performed using the external magnetic system to steer the capsule, while work is also underway to develop variants of the vibrating capsule, that employ the inductive powering scheme described in [14].

Acknowledgments

This work was supported in part by the European Community, through the FP6 IST R&D project VECTOR (contract number 0339970). The authors would like to acknowledge the contributions of the project partners in various aspects of the present work and Ekawahyu Susilo and Irene Del Chicca for their help in the development of the system components.

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Biographies

Gastone Ciuti received the master's degree in Biomedical Engineering from the University of Pisa, Pisa, Italy, in April 2008. He is currently working towards a Ph.D. degree in biorobotics at The BioRobotics Institute, Scuola Superiore Sant'Anna, Pisa. His current research interests include robotic endoscopy and robotic surgery, and design of platform and capsule robots for biomedical applications.

Nikos Pateromichelakis received his bachelor degree at the Technological Educational Institute of Crete in 2004, at the Department of Mechanical Engineering, with a major in Mechatronics. In 2006 he completed the Master of Science in Mechatronics at FH Aachen, Germany. Since 2007 he has been working as an R&D Engineer at the Computational Vision and Robotics Laboratory at ICS-FORTH, participating in many research programs. He has experience in Computer Aided Design and rapid prototyping technologies, in the design of electronic circuits, in the programming of microprocessors, as well as in the development of low-level control systems for robotic mechanisms.

Michael Sfakiotakis received his Bachelor's degree in Electrical Engineering from Aristotle University, Thessaloniki, Greece, in 1995; his M.Sc. degree in Communications, Control and DSP from Strathclyde University, Glasgow, U.K., in 1996; and his Ph.D. degree in Electrical Engineering from Heriot-Watt University, Edinburgh, U.K., in 2000. He is Assistant Professor at the Dept. of Electrical Engineering of the Technological Educational Institute (T.E.I.) of Crete, Greece, teaching a number of courses on control systems, robotics and microcontroller applications. He is also an Associated Researcher at the Institute of Computer Science of FORTH, Greece, where he is involved in a number of EU-funded projects. His main research interests are in the areas of biologically inspired robotics and biomedical robotic systems.

Pietro Valdastri received a degree in electronic engineering (with honours) from the University of Pisa in February 2002. In the same year he joined the CRIM Lab of the Scuola Superiore Sant'Anna in Pisa as a Ph.D. student. In 2006 he obtained a Ph.D. in bioengineering from the Scuola Superiore Sant'Anna discussing a thesis titled "Multi-Axial Force Sensing in Minimally Invasive Robotic Surgery". After spending three years as Assistant Professor at the Institute of Biorobotics of Scuola Superiore Sant'Anna, he is now Assistant Professor at the Department of Mechanical Engineering at Vanderbilt University, where he founded the STORM Lab. He is actively involved in robotic endoscopy and robotic surgery, designing of magnetic mechanisms, and design of capsule robots for biomedical applications.

Arianna Menciassi received her laurea degree in physics (with honours) from the University of Pisa in 1995. In the same year, she joined the Scuola Superiore Sant'Anna in Pisa as a Ph.D. student in bioengineering and she obtained the Ph.D. degree in 1999. Currently she is a professor of biomedical robotics at the Scuola Superiore Sant'Anna, Pisa. Her main research interests are in the fields of biomedical micro and nano-robotics, surgical robotics, mechatronics and microsystem technologies. She is working on several European projects and international projects for the development of robotic systems for therapeutic, diagnostic and surgical applications.

Dimitris P. Tsakiris received his Ph.D. degree in electrical engineering from the University of Maryland at College Park, USA, in 1995. Subsequently, he was a Marie Curie postdoctoral fellow at the Institut National de Recherche en Informatique et en Automatique (INRIA) in Sophia-Antipolis, France. He has been with the Institute of Computer Science of the Foundation for Research and Technology–Hellas (FORTH) in Heraklion, Greece, since 1999, where he is currently a principal researcher. He is also a faculty member of the Graduate Program in the Brain and Mind Sciences of the University of Crete in Heraklion, Greece. His research interests lie in the areas of robotics, nonlinear control, geometric mechanics and computational vision, and in biologically inspired approaches to robotic locomotion, control and sensing. He is a principal investigator and co-investigator of several European projects related to the above research areas.

Paolo Dario received his Dr. Eng. Degree in Mechanical Engineering from the University of Pisa, Italy, in 1977. He is currently Professor of Biomedical Robotics at the Scuola Superiore Sant'Anna in Pisa. He is the Director of the BioRobotics Institute of Scuola Superiore Sant'Anna, where he supervises a team of about 120 researchers and Ph.D. students, and the Director of Polo Sant'Anna Valdera. His main research interests are in the fields of medical robotics, bio-robotics, mechatronics and micro/nanoengineering, and specifically in sensors and actuators for the above applications, and in robotics for rehabilitation. He is the coordinator of many national and European projects, the editor of two books on robotics, and the author of more than 250 scientific papers (more than 150 on ISI journals). Prof. Dario has served as President of the IEEE Robotics and Automation Society in the years 2002–2003 and he is an IEEE Fellow, a Fellow of the European Society on Medical and Biological Engineering, and a recipient of many honours and awards, such as the Joseph Engelberger Award.