Workshop

Robotic endoscopic capsules for gastrointestinal screening, diagnosis and therapy: achievements and future challenges

Organisers: G. Ciuti, J. M. Dias

http://sssa.bioroboticsinstitute.it/workshops/REC2015

This workshop is supported by IEEE RAS Technical Committee on Surgical Robotics

Objectives

Gastrointestinal endoscopy dates back to the 1860s, but many of the most significant advancements have been made within the past decade. Wireless capsule endoscopy (WCE), a revolutionary clinical alternative to traditional flexible scopes, enables inspection of the digestive system with minimal discomfort for the patient or the need for sedation, mitigating some of the risks of flexible endoscopy. Although WCE has entered the medical scene as a disruptive technology, it presents a number of limitations, *e.g.*, the impossibility to actively control locomotion and camera orientation, which leads to low diagnostic specificity and false-positive results. Therefore, the natural evolution of clinical WCE consists of integrating mechanisms for closed-loop active locomotion and providing the capsule with sensors and tools for diagnosis and therapy.

In the workshop, a wide range of open challenges about robotic endoscopic capsule will be addressed. Ranging from active locomotion mechanisms to sensing and therapeutic modules, the topics of interest will cover key aspects of smart robotic devices for gastrointestinal procedures. In the morning, a keynote presentation of Prof. Paolo Dario (The BioRobotics Institute, Scuola Superiore Sant'Anna) is followed by three technical sessions: i) capsules and novel flexible endoscopic devices, ii) robotic locomotion for active endoscopic capsules and iii) sensing and therapeutic modules. The current and future challenges will be discussed in a panel discussion with all invited speakers and the attendees of the workshop.

To represent the current research trends, we design a combination of invited talks: invited speakers will include expert researchers with an engineering and medical background, medical doctors but also companies.

Topics of interest

- Endoscopic capsules for gastrointestinal procedures;
- Locomotion and localization methodologies for endoscopic capsules;
- Physical simulations, magnetic modelling and FEM;
- Sensing, telemetry and data communication;
- Motion planning and autonomous/assisted diagnosis and therapy;
- Mesoscale mechanisms for diagnosis and therapy delivery;
- Power supply and innovative energy solutions for endoluminal robots;
- Flexible endoscopes and applications, medical and not.

Invited Speakers:

1. P. Dario, The BioRobotics Institute, Scuola Superiore Sant'Anna (R)
2. G. Ciuti, The BioRobotics Institute, Scuola Superiore Sant'Anna (R)
3. M. Keuchel, Bethesda Krankenhaus Bergedorf (MD)
4. A. Arezzo, University of Turin (MD)
5. A. Koulaouzidis, The Royal Infirmary of Edinburgh (MD)
6. M. Visentini-Scarzanella, Kagoshima University (R)
7. V. Seetohul, University of Dundee (R)
8. Jong-Oh Park, Chonnam National University (R)
9. P. Valdastri, Vanderbilt University (R)
10. D. Iakovidis, Technological Educational Institute of Central Greece (R)
11. G. Kosa, Tel Aviv University (R)
12. M. Q.-H. Meng, The Chinese University of Hong Kong (R)
13. M. Vatteroni, EYE-TECH company (IND)
14. T. Nowak, MEDTRONIC company (IND)

(R): university researcher, (MD): medical doctor, (IND): industrial

Program

Time	Talk
8:30 - 9:30	**Welcome (opening) and Keynote speech**
	Prof. P. Dario (R), The BioRobotics Institute, Scuola Superiore Sant'Anna - **Robotic Endoscopic Capsules: achievements and challenges**
9:30 - 10:00	**Poster Teaser Session**: a set of brief (5 minutes) presentations for each poster
10:00 - 10:30	**Coffee Break**
10:30 - 11:30	**Session 1: Capsules and novel flexible endoscopic devices** (Chair: G. Ciuti)
10:30 - 10:50	**Dr. M. Keuchel** (MD), Bethesda Krankenhaus Bergedorf - **Flexible technologies for endoscopic procedures: current achievements and medical perspectives**
10:50 - 11:10	**Prof. A. Arezzo** (MD), University of Turin - **Capsule-based endoscopy: from current achievements to open challenges**
11:10 - 11:30	**Dr. A. Koulaouzidis** (MD), The Royal Infirmary of Edinburgh - **Would active capsule endoscopy be a "nice solution" in 2020?**
11:30 - 12:30	**Poster Session**
12:30 - 13:30	**Lunch Break**
13:30 - 13:50	Industrial view by **EYE-TECH company - Dr. Monica Vatteroni - High dynamic range image sensors for biomedical applications**
13:50 - 14:50	**Session 2: Robotic locomotion for active endoscopic capsules** (Chair: A. Menciassi)

13:50 - 14:10	**Dr. G. Ciuti** (R), The BioRobotics Institute, Scuola Superiore Sant'Anna - **Active capsule endoscopy for screening, diagnosis and treatment**
14:10 - 14:30	**Prof. Jong-Oh Park** (R), Chonnam National University - **Mechanical mechanism and principles for active capsule locomotion**
14:30 - 14:50	**Dr. G. Kosa** (R), Tel Aviv University - **Advances in self-propulsion of internally driven capsule endoscopes**
14:50 - 17:00	**Session 3: Sensing and therapeutic modules** (Chair: J. M. Dias)
14:50 - 15:10	**Dr. P. Valdastri** (R), Valderbilt University - **Systematic Design of Medical Capsule Robots**
15:10 - 15:30	**Dr. D. Iakovidis** (R), Technological Educational Institute of Central Greece - **Automatic lesions detection for wireless capsule endoscopy**
15:30 - 16:00	**Coffee Break**
16:00 -16:20	**Dr. M. Visentini-Scarzanella** (R), Kagoshima University - **One-shot techniques for 3D reconstruction in flexible and capsule endoscopy for diagnosis and navigation**
16:20 - 16:40	**Prof. M. Q.-H. Meng** (R), The Chinese University of Hong Kong - **Wireless capsule endoscopy: from localization to automatic diagnosis**
16:40 - 17:00	**Dr. V. Seetohul** (R), University of Dundee - **Robotic requirements for diagnosis and therapy with ultrasound capsule endoscopy**
17:00 - 17:20	Industrial view by **MEDTRONIC company - Dr. Tanja Nowak - Deep Dive into Capsule Endoscopy from a company's point of view**
17:20 - 18:00	**Panel Discussion and Summary** (Chairs: A. Menciassi, G. Ciuti and J. Dias): A panel discussion involving experts on robotics and participants from academia, clinics and industry to summarize the state of the art and highlighting the still open research issues, particularly with respect to clinical applications and industrial commercialization. Non medical applications will be also considered and discussed (*e.g.*, pipes inspection).
18:00	**End**

Keynote speech

Prof. P. Dario (R)
The BioRobotics Institute, Scuola Superiore Sant'Anna

Robotic Endoscopic Capsule: achievements and challenges

While surgical robots become well-established clinical practice, the need for better instruments (less invasive, less bulky, more functional and cheaper), arises. This motivates a quest for miniaturization and for dexterity in a new generation of low access trauma and surgical instruments and robots usable in endoscopic diagnosis and in novel surgical procedures such as N.O.T.E.S. and single-port laparoscopy.
In this lecture, the development of endoluminal robotics instruments will be illustrated, with reference to actuated worm-like devices for painless colonoscopy, to wireless and wired robotic capsules for interventional endoscopy in the gastrointestinal tract, and to the frontier of millimetre-size capsules for peripheral blood vessels.

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 has been visiting researcher and professor at Brown University, USA, at EPFL, Switzerland, at College de France, France, at Polytechnic University of Catalunya, Spain, at Zhejiang University, China, at Waseda University, Japan, and at Khalifa University, Abu Dhabi, United Arab Emirates.
He is the Director of the BioRobotics Institute of Scuola Superiore Sant'Anna, where he supervises a team of about 150 researchers and Ph.D. students, and the Director of Polo Sant'Anna Valdera, a Research Center located in Pontedera (Pisa, Italy). 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 500 scientific papers (more than 250 on ISI journals). He is Editor-in-Chief, Associate Editor and member of the Editorial Board of many international journals. He has been a plenary invited speaker in many international conferences.
Prof. Dario has served as President of the IEEE Robotics and Automation Society in the years 2002-2003. He has been the General Chair of the BioRob'06 Conference (The First IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics), of ICRA 2007 (International Conference on Robotics and Automation), ISG 2008 (the 6th Conference of the International Society for Gerontechnology) and of the First National Congress of Bioengineering (GNB 2008).
Prof. Dario is an IEEE Fellow, a Fellow of the European Society on Medical and Biological Engineering, and a recipient of many honors and awards, such as the Joseph Engelberger Award. He is also a member of the Board of the International Foundation of Robotics Research (IFRR). In 2009 He has been appointed Fellow of the School of Engineering of the University of Tokyo.

Session 1: Capsules and novel flexible endoscopic devices (Chair: G. Ciuti)

Dr. M. Keuchel (MD)
Bethesda Hospital Bergedorf, Hamburg, Germany

Flexible technologies for endoscopic procedures: current achievements and medical perspectives

Flexible endoscopy is an integral diagnostic and therapeutic tool in clinical gastroenterology. High quality standards for safety, patients comfort and efficiency have been achieved. Colonoscopy as gold-standard for colorectal cancer screening includes prophylactic removal of detected adenomas as precursors of cancer.
High resolution gastrointestinal (GI) endoscopes are commercially available. Additional features for enhanced characterisation of mucosal and vascular patterns are virtual chromoendoscopy, zoom, confocal laser microscopy, endocytoscopy, and autofluorescence. Additional cameras can enlarge the viewing field. Endoscopic ultrasound visualizes also deeper layers.
Possibility of luminal cleansing is a major advantage of flexible GI endoscopy. Applying various devices through the working channel enables staining, biopsies, injection, polypectomy, submucosal dissection, clipping, coagulation, dilation, and stenting. Large clips or band-ligators are attached to the endoscope tip.
Self-propelled colonoscopes may provide painless sedation-free endoscopy.
Ballon or spiral overtube devices assist in deep enteroscopy of the small bowel or incomplete colonoscopy. External caps, flaps, balloons or wheels may optimize endoscope position.
Procedural limitations of flexible endoscopy are rare, including incomplete investigation, patients´ discomfort, complications as perforation, and risks of sedation. However, frequent reluctance to screening colonoscopy and cumbersome flexible enteroscopy of the mid small bowel demand further research to improve alternative minimally invasive wireless technologies.

Dr. Martin Keuchel is Head of the Department of Internal Medicine at Bethesda Hospital Bergedorf, Hamburg, Germany. He obtained a BSc (Vordiplom) in Biology at JW Goethe University in Frankfurt (1980) and his Medical Doctorate from Philipps University Marburg Germany at the Institute of Experimental Immunology (1987). He was a fellow in Internal Medicine, Nephrology, Intensive Care and Transplantation at University of Marburg, in Infectiology at Bernhard Nocht Institute for Tropical Medicine, and in Gastroenterology at Asklepios Klinik Altona, Hamburg. He has a diploma in Tropical Medicine (1991) and Board certification in Internal Medicine (1993), Nephrology (1997), and Gastroenterology (2002). He received the venia legendi at Semmelweis University, Budapest, Hungary with his habilitation on optimizing video capsule endoscopy and he is a lecturer at Asklepios Campus Hamburg in Gastroenterology. He is a fellow of the European Board of Gastroenterology and Hepatology.

Prof. A. Arezzo (MD)
University of Turin

Capsule-based endoscopy: from current achievements to open challenges

Colorectal cancer (CRC) is responsible for >600.000 deaths worldwide. The survival rate increases for early stages, which recommends regular screening over 50 years old. To date, conventional colonoscopy is considered to be the most effective method for CRC diagnosis and screening. However, take–up of screening colonoscopy is limited due to a variety of factors including invasiveness, patient discomfort, fear of pain, and the need for sedation. The technology behind standard optical colonoscopy basically consists of a long semirigid tube with a steerable head, relatively stiff compared with the compliant nature of the colon; as a result of this “back–wheel drive” approach, looping occurs during insertion leading to pain and potential tissue damage or even perforation. Colon capsule endoscopy (CCE) and innovative robotic colonoscopes solve the drawbacks of pain and discomfort, but lack in reliability and diagnostic accuracy and fail due to inability to combine therapeutic functionalities with the common screening purposes. Key factors for success are: 1. The capability to reproduce a painless procedure for high acceptance by patients in mass screening; 2. ease to perform (due to robotic teleoperated guidance, diagnosis and therapy and embedded control capabilities, – reduction of required skills and thus standardization of procedure); 3. tremendous social benefit and reduced cost for the public healthcare systems.

Prof Alberto Arezzo is Associate Professor at the University of Torino, Italy. Since the beginning of his career he is serving both as conventional endoscopist and endoscopic surgeon. Member of the Technology Committee of the European Association for Endoscopic Surgery (EAES) and of the Board of the Society for Medical Innovation and Technology (SMIT) and of the Italian Society for Digestive Endoscopy (SIED). Former scientist at the Section for Minimally Invasive Surgery at Eberhart Karls University of Tuebingen, Germany. Consultant in the field of Endoscopic Surgery and Flexible Endoscopy of Ethicon Endosurgery (Johnson & Johnson Medical), Boston Scientific, Microvasive Endoscopy, Karl Storz Endoskope GmbH. Partner of different FP5/FP6/FP7 projects CLEANTEST, VECTOR and STIFF- FLOP. He has been Coordinator of several international multicentre studies and projects. He is the Founder of the start-up company RED, Robot for Endoscopic Dissection. Prof Arezzo is Teacher of Emergency Surgery at the VI year of the School of Medicine and teacher or tutor of courses at the School of Surgery, such as Scientific English, Surgical Anatomy and Digestive Surgery. He is the Vice-Coordinator of the PhD Course in Technology Applied to Surgical Sciences. He is Faculty and Tutor of the II Level University Master course in Advanced Laparoscopy for MDs. He is Coordinator, Faculty and Tutor of the II Level University Master course in Operative Digestive Endoscopy for MDs.

Dr. A. Koulaouzidis (MD)
The Royal Infirmary of Edinburgh

Would active capsule endoscopy be a "nice solution" in 2020?

Capsule endoscopy (CE) is a major breakthrough and an invaluable supplement to conventional endoscopy. However, it will require further development as major drawback of current, commercially-available CE models, is their passive locomotion [1,2]. In the near future, we will continue to see novel steering and actuation techniques, and further development of existing soft-tethered capsules [1,3]. Magnetic locomotion seems to be the favorable method for untethered control of CE actuation [1,4]. Furthermore, optical enhancing techniques, such as improved image resolution, contrast and tissue penetration and provision of biochemical and molecular information could lead to -in situ- optical (instead of mechanical) biopsy [1,5]. Power consumption continues to be a relevant challenge, which is limited by the size of the capsule [1]. Volume/size compression can be achieved, as the technological frenzy of our days will eventually lead to the production of remarkable small parts and this might allow the production of dissolvable capsules, including the use of non- toxic batteries [6]. The mainstream small bowel endoscopy in the third decade of the new millennium should be provided by an enhanced, next-generation capsule-based platform, such as the one proposed by Iakovidis et al [5]. Furthermore, computational methods that can be implemented in software can enhance the diagnostic yield of CE both in terms of efficiency and diagnostic accuracy [7]. However, in an 'remote' environment like the small-bowel, the attention should focus on how to utilize the existing carrier shape and size, but with miniaturized components such as microscopic batteries, that will leave internal space and provide enough power for internal lens rotation, space for microscopic labs (lab-in-a-pill) and other sensing capacities and -hopefully- deliver powder medication for bleeding [2].

Dr. Anastasios (a.k.a Tassos) Koulaouzidis is Associate Specialist in the Centre of Liver and Digestive Disorders at the Royal Infirmary of Edinburgh, clinical lead of the capsule endoscopy service, and Honorary Clinical Fellow of School of Clinical Sciences, the University of Edinburgh, Scotland, UK. He obtained his MD from the Medical School of the Aristotle University of Thessaloniki (Greece) in 1995 and his Doctorate in Medicine from the University of Edinburgh (2014) with the title "Optimising the use of capsule endoscopy in the detection of small-bowel pathology". He is currently working towards his Doctorate in Philosophy (on innovative aspects of capsule endoscopy) at the university of Lund, Sweden. Dr Koulaouzidis became a Member of the Royal College of Physicians of Edinburgh (UK) in 2004 and a Fellow of the same College in 2013. He is also a Fellow of the European Board of Gastroenterology (2009), the Royal Society for Public Health (2013) and the American College of Gastroenterology (2015). He is the co-author of three book chapters and more than 100 PubMed articles, out of which at least 40 are on capsule endoscopy. His research interests include clinical applications of capsule endoscopy, quality improvement and software diagnostics as well as hardware and concept development in capsule endoscopy. Other specialty interests include colonoscopy, microscopic colitis, and conventional (as well as minimally-invasive) small-bowel endoscopy. He is member of the editorial and/or advisory board of several specialty journals and associate editor or Editor-in-Chief of three Gastroenterology/Hepatology journals. Dr Koulaouzidis was awarded the Given®Imaging-ESGE Research Grant 2011, a University of Edinburgh Innovation Initiative Grant in 2011 and one of the ESGE Postgraduate Visiting Fellow Grants (2010). His full profile is available via the following site: www.drkoulaouzidis.com.

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Dr. Monica Vatteroni (IND)

Industrial view by **EYE-TECH company (Chairs: G. Ciuti)**

High dynamic range image sensors for biomedical applications

HD CMOS image sensor with tunable dynamic range for disposable endoscopic applications

The continuous quest for painless diagnostic procedures has resulted in greater interest in endoluminal techniques for several body districts. To reduce the invasiveness of the procedures and improve the diagnostic capability of the devices, it is mandatory to develop new mechanical, electronic and optical parts to be integrated in more and more miniaturized devices. About vision systems, the new trend is chip-on-tip technology. To make this possible, the interest on CMOS imagers is increasing, because of the possibility for deep miniaturization, easy control and reduced costs. However, the offering for CMOS image sensors for the biomedical-endoscopic market is quite limited and the use of non-optimized sensors, designed for other applications, diffused.
In this abstract, EYETECH_1080, a CMOS image sensor designed for disposable biomedical endoscopic applications, is proposed. The sensor presents High Dynamic Range (HDR) capability in a controlled light environment to avoid saturated regions (EYE-TECH IP). The fabricated chip is a color RGB imager compliant with full HD standard. The complete functionality of the chip is through 9 signal pins. Because of the HDR capability in controlled light environments and the good noise performance the image quality is comparable to CCD performance with the advantage of the high system integration.

Monica Vatteroni was born in La Spezia, Italy, in 1975. She received the M.S. degree in electrical engineering from the University of Pisa, Pisa, Italy, in 2001, and the Ph.D. degree in physics from the University of Trento, Trento, Italy, in 2008. She has 15 years of experience both in the industry and the academy in the field of CMOS imager design and endoscopic biomedical applications. She has collaborated with companies like ST Microelectronics and EUROTECH S.p.A. In the research field she still have active collaborations with The BioRobotics Institute of Scuola Superiore Sant'Anna, Pisa, Italy, and the ISA institute of Université Claude Bernard, Lion, France. Presently Dr. Monica Vatteroni is co-founder and research and development manager in EYE-TECH s.r.l. where she is responsible for the research and development of CMOS image sensors mainly for biomedical applications.

Session 2: Robotic locomotion for active endoscopic capsules (Chair: A. Menciassi)

Dr. G. Ciuti (R)

The BioRobotics Institute, Scuola Superiore Sant'Anna

Active capsule endoscopy for screening, diagnosis and treatment

Medical robots have a significant potential to fundamentally change surgery and interventional medicine as part of a broader, information-intensive environment that exploits the complementary strengths of humans and computer-based technologies. Robots for surgery are computer-integrated systems in which the device / tool itself is just one element, i.e. the end-effector, of a larger system designed to assist a physician in carrying out a diagnostic / surgical procedure. The research field of computer-integrated technologies for robotic surgery is focusing on this effort by advancing the computer-assisted scenario efficiently merging medicine and engineering.
Endoscopy dates back to the 1860s, but many of the most significant advancements have been made within the past decade. With the integration of robotics, the ability to precisely steer and advance traditional flexible endoscopes has been realized, reducing patient pain and improving clinician ergonomics. Additionally, wireless capsule endoscopy, a revolutionary alternative to traditional scopes, enables inspection of the digestive system with minimal discomfort for the patient or the need for sedation, mitigating some of the risks of flexible endoscopy. In this talk Dr. Gastone Ciuti will present the main elements for investigating problems, identifying enabling technologies and developing solutions for addressing the field of capsule endoscopy for what concern active locomotion for screening, diagnosis and also treatment. Different solutions (focused on mechanical and magnetic actuation) will be presented in this talk ranging from legged-based solutions to magnetic locomotion (permanent and electromagnetic systems).

Gastone Ciuti received the master's degree (with honours) in Biomedical Engineering from the University of Pisa, Italy, in 2008 with a thesis entitled "Study and development of endoscopic robot with locomotion based on permanent magnetic field", carried on at CRIM (Center for Research in Microengineering) Lab of Scuola Superiore Sant'Anna, Pisa, Italy, and winning the 8th edition of the Master Thesis Price of the National group of Bioengineering at the summer school in Bressanone, Italy in 2008. In the same year he joined the Scuola Superiore Sant'Anna in Pisa as a Ph.D. student and in 2012 he obtained the Ph.D. in Innovative Technologies of Info. & Com. Eng. and Robotics at The BioRobotics Institute of the Scuola Superiore Sant'Anna discussing a thesis entitled "Innovative control platform for robotic microsystems in endoluminal surgery". Gastone Ciuti is currently an Assitant Professor at The BioRobotics Institute of Scuola Superiore Sant'Anna, Surgical Robotics and Allied Technologies group and head of the Computer-Integrated Technologies for Robotic Surgery laboratory (from January 1st, 2014). In 2013 he performed an Executive Master in Project Management learning issues significant for the possible definition of National and International research projects. Since 2011 to present Gastone Ciuti performs teaching activity in the course "Medical Robotics" held Prof. Paolo Dario at the University of Pisa and in October 2013 Gastone Ciuti was designed "Cultore della Materia" in Medical Robotics. Gastone Ciuti was an exchange researcher at FORTH - Institute of Computer Science, Heraklion, Crete, Greece in 2009, at MED Lab, Vanderbilt University, Nashville, Tennessee, USA in 2010 and at The Hamlyn Centre, Imperial College London, London, UK in 2012. Gastone Ciuti supervised sevral master students; he was the technical mentor of three students (one within a Fulbright Scholarship program) and the technical tutor of a PhD student in Biorobotics at the BioRobotics Institute of SSSA. Gastone Ciuti is co-autor of about 35 scientific publications on computer-integrated platforms and innovative devices for medical robotic intervention and treatment and he is also inventor of 7 patents.

Prof. Dr.-Ing. Jong-Oh Park **(R)**
Robot Research Initiative, Chonnam National UNiversity

Mechanical mechanism and principles for active capsule locomotion

We proposed a novel electromagnetic actuation(EMA) system that can realize a 3D locomotion and a steering within the digestive organs. The proposed active locomotion intestinal capsule endoscope (ALICE) consists of five pairs of solenoid components and a capsule endoscope with a permanent magnet. With the magnetic field generated by the five pairs of solenoid components, the capsule endoscope performs various movements necessary for the diagnosis of the gastrointestinal tract, such as propulsion in any direction, steering, and helical motion. From the results of the basic locomotion test, ALICE showed a propulsion angle error less than 4° and a propulsion force of 70 mN. To further validate the feasibility of ALICE as the diagnostic tool, we executed ex-vivo testing using small intestine extracted from a cow. Through the basic mobility test and the ex-vivo test, we could verify ALICE's usability as a medical capsule endoscopic system. In addition, biopsy function for the histological examination of digestive diseases was necessary to add. We proposed a novel robotic biopsy module for ALICE. The proposed biopsy module has a sharp blade connected with a shape memory alloy actuator. The biopsy module with 12mm in diameter and 3mm in length was integrated into ALICE prototype, where the module's sharp blade was activated and exposed by the shape memory alloy actuator. EMA system could generate the specific motion of ALICE prototype to extract a tissue sample from the intestinal walls. Through an in-vitro test, the sampled biopsy tissue had a volume of about $6mm^3$, which is a sufficient amount for a histological analysis. Consequently, we proposed the working principle of the biopsy module and conducted the in-vitro biopsy test to verify the feasibility of the biopsy module integrated into the ALICE prototype using the EMA system.

Jong-Oh Park received master degree in mechanical engineering from KAIST in1981 with the thesis of "Optimal design of hip prosthesis". He finished Dr.-Ing. from Stuttgart University with the thesis "untersuchung des Plasmaschneidens zum Gussputzen mit Industrierobotern" in 1987. In parallel he has worked as a guest researcher at Fraunhofer-Institut fuer Produktionstechnik und Automatisierung (FhG-IPA) in Stuttgart, Germany until 1987. He moved to Korea Institute of Science and Technology and has joined in robotics and automation as a senior/principle engineer until 2005. From 1999 until 2004 he was a program director of "21C Frontier Research Program. His final target was to develop capsule endoscope and micro PDA in wrist watch form. He succeeded in colonoscope robot with SSSA team in Pisa together. One Korean company Intromedic was founded through the technology transfer of capsule endoscope from him. He moved to Chonnam National University in Feb 2005. He succeeded in fine positioning and clot elimination in in-vivo test of therapeutic microrobot in artery of pig in 2010. He also succeeded in bacteria-based microrobot for tumor therapy in in-vivo test in 2013. He transferred technology of active capsule locomotion to one local company in 2015. He received "Scientist of the Year" twice in 2010 and 2013 in Korea. He was awarded with the Order of Science and Technology Merit from Korean government in 2013. And he received "Fraunhofer Medal" from Fraunhofer Gesellschaft in 2015 and "Golden Robot Award" from ABB in 1997. Until now 118 patents have been registered and 77 journal papers have been published. He founded Robot Research Initiative as the director and major focus lies in biomedical micro/nano robotics and biorobotics.

Dr. G. Kosa (R)
Tel Aviv University

Advances in self-propulsion of internally driven capsule endoscopes

Microrobots have great potential for enabling interventional and diagnostic medical procedures. We define a microrobot as a power autonomous robot sizing under 5 cm^3 to 10 mm^3 capable of positioning itself and sensing and manipulation of its environment.
One of the greatest challenges in capsule endoscopy is intra-body self-propulsion. The easiest and the least energy consuming locomotion method in the body is swimming in a fluidic environment. Although in the scale of cm3 one can use propulsive systems that are used in regular sized systems such as propellers driven by electrical motors, the down-scaling of such systems is not favorable because the change in the flow regime and technological difficulties. Novel actuation methods have to be used for micro robots.
In RBM2S we are developing swimming actuators based on piezoelectric and magnetic operating principals. We developed multimorph piezoelectric benders that are capable of propelling an upscaled pill like structure in 3 DoF. In addition we are working swimming actuators in which the piezoelectric structure is divided into several sections that serve as piezoelectric sensors and actuators. We designed an adaptive control method to move in highly viscous fluids using these structures.
We are also continuing the research on magnetic actuators that are driven by the MRI. We developed a power autonomous command and control unit for magnetic swimmers that operates in 3 T magnetic field.

Gabor Kosa born in 1972 Szatmar-Nemeti, Transilvania, Romania. He received his B.Sc. degree cum laude in mechanical engineering from the Technion in Haifa, Israel in 1995. From 1995 to 1998, he served in the Israel Defense Force (IDF) as a research engineer. In 2001, he received his M.Sc. degree in non-linear dynamics and control from the Technion. He was employed in RAFAEL, the Armament Development Authority, in Haifa from 2000 to 2001 as a research and development engineer of MEMS. He received his Ph.D. in the field of micro-robots for medical application from the Technion in 2007. He was post-doc in the Computer Vision Laboratory in ETH Zurich, Switzerland working on novel sensing for haptics, swimming micro robots, leading the biomedical micro systems group. Currently he is senior lecturer at the School of Mechanical Engineering in Tel Aviv University and head of the laboratory of Robots and BioMedical Micro Systems (RBM2S) and the Education Robotics Laboratory (ERL). His research projects are in the field of Micro Systems and Micro Robots for biomedical applications, Medical Robotics, Bio Inspired Sensing Systems and Robots. His expertise is in micro robotics, sensing and actuation, micro fluidics, piezoelectricity, dynamics and control.

Session 3: Sensing and therapeutic modules (Chair: J. M. Dias)

Dr. P. Valdastri (R)
Valderbilt University

Systematic Design of Medical Capsule Robots

Over the last decade, researchers have explored the design space of medical capsule robots: devices that operate autonomously within the human body and can monitor, diagnose, prevent, and cure diseases. Medical capsule robots are severely resource constrained devices in size, power, and computational capacity. As such, the design process is time consuming and requires deep expertise in multiple domains. To open up the field and unlock the vast clinical potential of these devices as diagnostic and interventional tools, this talk will introduce an open source platform consisting of a library of modular hardware and software components and a web-based collaborative design environment. This work is currently supported by the Cyber-Physical Systems program of National Science Foundation. Preliminary results are reported in DOI: 10.1109/MDAT.2015.2459591 and DOI: 10.5772/59505.

Pietro Valdastri graduated cum Laude in Electrical Engineering from University of Pisa in 2001 and received a PhD cum Laude in Biomedical Engineering from Scuola Superiore Sant'Anna in 2006 with Paolo Dario as primary advisor. After spending three years as Assistant Professor at the BioRobotics Institute of Scuola Superiore Sant'Anna, focusing on implantable medical devices and surgical robotics, in 2011 he moved his research to Vanderbilt University, Nashville, TN. He is currently Assistant Professor of Mechanical Engineering, with secondary appointments in the Electrical Engineering Department and in the Division of Gastroenterology, Hepatology and Nutrition at Vanderbilt University Medical Center. Dr. Valdastri is the founder and director of the Science and Technologies Of Robotics in Medicine (STORM) Lab (https://my.vanderbilt.edu/stormlab/), a standing member of the Vanderbilt Institutional Review Board, a Senior Member of IEEE, one of the Editors of IEEE ICRA from 2016 to 2018, and Associate Editor of the Journal of Medical Robotics Research. His current research – focusing on capsule robots for gastrointestinal endoscopy and abdominal surgery – is funded by the National Science Foundation, the Broad Foundation, and the National Institute of Health. Dr. Valdastri is co-author of more than 70 peer-reviewed journal publications, co-inventor of more than 30 patents and patent applications, co-founder of a successful medical start-up (WinMedical, www.winmedical.com), and the recipient of several prestigious awards in the field of medical robotics, including the NSF CAREER Award in 2015, the Sensys 2014 Best Paper Award, the OLYMPUS Best Laparoscopy/Robotic Paper Award 2013, the OLYMPUS ISCAS Best Paper Award 2012, the ASME Design of Medical Devices Conference Best Paper Award 2012, the Hamlyn Symposium on Medical Robotics Best Oral Presentation Award 2011, and the European Association of Endoscopic Surgery Best Technology Presentation Award 2011. Dr. Valdastri's research has been featured by main magazines in the field, including IEEE Spectrum, IEEE Transactions on Biomedical Engineering, Medgadget, Medical Design Technology Magazine, Medical Xpress, Newswise, NSF Science Now.

Dr. D. Iakovidis (R)
Technological Educational Institute of Central Greece

Automatic lesions detection for wireless capsule endoscopy

Despite the technical progress to date, lesion detection and diagnosis in wireless capsule endoscopy relies heavily on the capabilities of the WCE video reviewers. The review process is challenging for the limited human capabilities of the reviewers as it demands intense focus and undistracted attention for inspection of a significantly large data volume (which is of the order of 50,000-120,000 images). Machine-based automatic lesion detection is essential for the reduction of false negative diagnoses, which can occur during this process. Indirectly, it can contribute to the reduction of the wireless capsule endoscopy video review-times. The consequent reduction of morbidity and healthcare costs can have a significant socioeconomic impact.
The main challenge in the development of automatic lesion detection methods is to identify and mathematically model the image features that differentiate lesions from normal mucosa (and intestinal content), while the diversity of the lesions makes the problem of automatic lesion detection an even more challenging task. Close collaboration between health professionals and information technology scientists, as well as pubic availability of annotated WCE datasets can contribute to an essential progress in this research direction.

Prof. Dimitris K. Iakovidis (http://is-innovation.eu/home/members) received his BSc in Physics, MSc on Cybernetics, and PhD on Informatics from the University of Athens, Greece, in 1997, 2001 and 2004 respectively. Since then, he has gained significant experience from several research projects on imaging, uncertainty-aware decision support and intelligent systems. He has served as an Assistant and Associate Professor in the Department of Computer Engineering of the Central Greece University of Applied Sciences (Technological Educational Institute of Central Greece), and in 2015 he was elected Associate Professor at the Department of Computer Science and Biomedical Informatics of The University of Thessaly in Greece. Prof. Iakovidis has co-authored over 120 journals, conference papers, and book chapters. A significant part of his scientific contributions address computer-aided analysis of endoscopic video. These include pioneering approaches for automatic lesion detection, video reading time reduction and visualization for capsule endoscopy. He is also a Senior IEEE Member, Member of IAPR and EUCOG.

Dr. M. Visentini-Scarzanella (R)
Kagoshima University

One-shot techniques for 3D reconstruction in flexible and capsule endoscopy for diagnosis and navigation

Accurate intraoperative 3D reconstruction is a sensing challenge with great potential rewards. In externally controlled or self-propelled systems, it would allow dynamic path planning and locomotion control. For diagnosis, shape and size information is important to determine the correct course of action for treatment, e.g., of abnormal growths. Especially in the case of flexible and capsule endoscopy, where monocular devices are the norm, the endoscopist has to rely solely on visual cues in order to infer the shape and size information. However, tissue uniformity and scale ambiguity from traditional monocular endoscopes make this visual assessment prone to errors and time consuming. In this talk, we present one-shot techniques with the potential to help in this challenging problem. We cover both active and passive systems, ranging from recent advances in structured light probes for endoscopy to advances in photometric techniques such as Photometric Stereo and Shape-from-Shading, together with best practices for calibration.

Marco Visentini-Scarzanella is a JSPS Postdoctoral Fellow in the Computer Vision & Graphics Laboratory at the University of Kagoshima, Japan, researching active stereo systems for endoscopic 3D reconstruction and diagnosis. He received his MEng and Ph.D. degrees at Imperial College London in the Hamlyn Centre for Robotic Surgery in 2007 and 2012 respectively, while focusing on multiple visual cue integration for 3D reconstruction in minimally invasive surgery. He subsequently joined the Department of Electrical and Electronic Engineering at Imperial College London for a post-doctoral position in applications of computer vision for image and video forensics, as well as a visiting position at the Politecnico di Milano, Italy. He was recently awarded the 2015 Toshiba Fellowship at the Toshiba R&D Laboratories in Kawasaki, Japan, to continue his work on 3D reconstruction techniques applied to endoscopic navigation. His research in computer vision focuses on 3D reconstruction, shape-from-X and augmented reality for endoscopy and minimally invasive surgery.

Prof. M. Q.-H. Meng (R)
The Chinese University of Hong Kong

Wireless capsule endoscopy: from localization to automatic diagnosis

This talk will highlight our previous work on precision 3D position and orientation determination of wireless capsule endoscope, followed by our work on image-based automatic disease detection for wireless capsule endoscopy.

Dr. Max Meng is a professor of electronic engineering at the Chinese University of Hong Kong. His research interest is in medical robotics, perception and robotics, robot human interaction. He is a fellow of IEEE.

Resume of Career
Having held the positions of assistant professor (1994), associate professor (1998) and full professor (2000) in the Department of Electrical and Computer Engineering at the University of Alberta in Canada from 1994 to 2004, Professor Meng has been a Professor in the Department of Electronic Engineering at the Chinese University of Hong Kong since 2002. Professor Meng received his Ph.D. degree in Electrical & Computer Engineering at the University of Victoria in Canada in 1992, following his M.Sc. degree in Automatic Control at Beijing Institute of Technology in 1988. Professor Meng is a Fellow of IEEE.

Current Research Interests
Surgical robotics and medical devices, medical image based automatic diagnosis, information-enabled devices and systems, intelligent robotic system, sensors and information fusion, and related medical and industrial applications

Highlights of Recent Achievements
- Professor Meng's research group is among the first in research and development of active wireless capsule endoscopy and the related image-based automatic diagnosis.
- Professor Meng's research group won the best paper awards and best student paper awards at several international events including IEEE Robio, IEEE ICIA, and IEEE ICMA conferences.
- Professor Meng's research group members have been offered faculty positions at leading international and national universities.
- Professor Meng's research group has three Hong Kong PhD Fellowship Scheme recipients.

Dr. V. Seetohul (R)
Institute for Medical Science and Technology, School of Medicine, Ninewells Hospital and Medical School, Dundee, DD1 9SY

Robotic requirements for diagnosis and therapy with ultrasound capsule endoscopy

Research into the addition of ultrasound functionality to the now well-established video capsule endoscopy (VCE) is under way in various places around the world. Such ultrasound capsule endoscopy (USCE) brings with it additional demands relating to the possibility for robotic control of the capsule. These relate to three specific features of USCE devices under development in the UK EPSRC-funded Sonopill programme. First, the capsule may be tethered or untethered, with the former providing direct physical means of delivery of power and control signals and therefore the best proximate target for research. Second, as an ultrasound device, the capsule requires a continuous soft solid or liquid path to the region of the gut wall subject to imaging. Limited research to date suggests that this is relatively straightforward to achieve, at least in an intermittent fashion. Third, ultrasound offers the potential for both imaging and therapy, with the latter making stronger potential demands on the dexterity of the robotic solution that is required, for example to allow the capsule to be established in a static position relative to a particular area of the gut wall to allow treatment to take place. In this paper, we explain these key differentiating features and consider their impact on the requirements of robotics for USCE.

Vipin Seetohul, Benjamin Cox and Sandy Cochran
The authors are members of the approximately 30-strong Sonopill programme team, which is led by Prof. Cochran, with Dr Cox as Clinical Research Fellow and Dr Vipin Seetohul as a Postdoctoral Research Assistant in its Clinical Theme.
Prof. Cochran's expertise lies principally in ultrasound devices and systems, in which he has been an author of more than 250 journal and conference papers and presentations. Dr Cox has worked in various fields, most recently in focused ultrasound surgery with soft-embalmed cadavers and now in identifying and developing clinical targets for USCE. Dr Seetohul's PhD was awarded for work on technical aspects of ultrasound and he now has particular responsibility for pathfinder capsule development to allow rapid progress towards the testing of various aspects of USCE and other complementary modalities.

Dr. Tanja Nowak (IND)

Industrial view by **MEDTRONIC company (Chairs: G. Ciuti)**

Covidien/Medtronic GmbH Deutschland

Deep Dive into Capsule Endoscopy from a company's point of view

A new product – a new success?
Capsule Endoscopy is a minimally invasive technology that revolutionized small bowel diagnostics when it was launched in 2001. Meanwhile it is state of the art, in medical terms: gold standard for OGIB.
The technology itself opened a huge variety of diagnostic possibilities like a capsule for the colon, a capsule to be moved (magnetically guided), a capsule with different algorithms – still some markets need to be developed and further ideas to be approved.
Let's discuss about willingness to enter new fields of technology, to understand and deal with its Technology Readiness Level and limits – and about the challenge of its transfer into daily routine to enhance patient care and improve patient outcomes.
Medtronic's mission is "***To contribute to human welfare by application of biomedical engineering in the research, design, manufacture, and sale of instruments or appliances that alleviate pain, restore health, and extend life."***

Medical Director Europe – Gastrointestinal Solutions
Covidien / Medtronic GmbH

Born: in Germany, living in Hamburg
Diploma: in biology / cytology (technical skills: microscopy, TEM, SEM – FAU Erlangen)
Thesis: "Functionality and biocompatibility of the electrocatalytic, implantable glucose sensor" (Siemens, R&D)
Post-doc: University School of Medicine in Kumamoto, Japan (EU science and technology fellowship)
Career steps: Sales, CRA, product management, marketing
(areas: growth hormone, pain medication, diabetes – Pharmacia/Pfizer, GSK)
Since 2009: Capsule Endoscopy: Clinical Affairs – Regulatory – Quality
(Given Imaging/Covidien/Medtronic)

Panel Discussion and Summary (Chairs: A. Menciassi, G. Ciuti and J. Dias)

A panel discussion involving experts on robotics and participants from academia, clinics and industry to summarize the state of the art and highlighting the still open research issues, particularly with respect to clinical applications and industrial commercialization. Non medical applications will be also considered and discussed (e.g., pipes inspection).

Prof. Arianna Menciassi (h-index 37 Scopus) is Full Professor of Biomedical Robotics at SSSA and head of the Surgical Robotics and Allied Technologies area at The BioRobotics Institute.
She teaches regularly at SSSA and at the Pisa University. She carries on intense research and training activity at high level (e.g., master candidates in biomedical engineering, PhD students). She is normally tutor of more than 15 students. From 2013 she is Vice-Dean of the "Classe di Scienze Sperimentali" of SSSA.
Between 2013 and 2014, she was Visiting Professor at the École nationale supérieure de Mécanique et des Microtechniques of Besançon (France), in the FEMTO Institute, and also at the Université Pierre Marie Curie in Paris.
Her main research interests involve biomedical robotics, microsystem technology and micromechatronics, with a special attention to the synergy between robot-assisted therapy and micro/nanotechnology solutions. She carries on important activity of scientific management of several projects, European and extra-European, thus implying many collaborations abroad.
She was selected as one of the principal investigator of the daVinci Research Kit (DVRK) community that involves several prestigious research institutes receiving an open DVRK from Intuitive Surgical Inc.
She is co-author of more than 270 scientific publications (more than 150 on ISI journals) and 6 book chapters on biomedical robots and microtechnology. She is also inventor of 32 patents, national and international.
She is now Topic Editor in Medical Robotics of the International Journal of Advanced Robotic Systems; she is Co-Chair of the IEEE-RAS Technical Committee on Surgical Robotics. She is involved in the BioRobotics Technical Committee of IEEE-EMBC. In 2007 she received the Well-tech Award (Milan, Italy) for her researches on endoscopic capsules, and she was awarded by the Tuscany Region with the Gonfalone D'Argento, as one of the best 10 young talents of the region.

Prof. Jorge Dias has an "Agregação" (Habilitation) degree and a Ph.D. on Electrical Engineering by the University of Coimbra, specialization in Control and Instrumentation. Jorge Dias have been Associated Professor at the University of Coimbra with activities in the Department of Electrical Engineering and Computers (www.deec.uc.pt) and the Institute of Systems and Robotics (ISR) (www.isr.uc.pt) from the University of Coimbra (UC) (www.uc.pt).
Jorge Dias do research in the area of Computer Vision and Robotics and has contributions on the field since 1984. He has several publications in international journals, books, and conferences.
Jorge Dias has been teaching several courses on Computer Vision, Robotics, Automation and Electrical Engineering and Computer Science and supervised several Ph.D. and Master students in the field of Computer Vision and Robotics. Jorge Dias was been principal investigator from several research international projects.
Jorge Dias coordinated the Mobile Robotics Laboratory from Instituto of Systems and Robotics and the Laboratory of Systems and Automation (LAS) (http://las.ipn.pt) from the Instituto Pedro Nunes (IPN) (www.ipn.pt). Instituto Pedro Nunes (IPN) is a technology transfer institute from University of Coimbra. Jorge Dias it was Vice-President from the Instituto Pedro Nunes (IPN) since June 2008 to June 2011. Since July 2011, Jorge Dias is acting as Associate Professor from ECE/Robotics at Khalifa University (UAE) at Abu Dhabi.

Introduction to the Papers

Papers (1-page contributions) have been submitted to the workshop "Robotic endoscopic capsules for gastrointestinal screening, diagnosis and therapy: achievements and future challenges“. The papers report interesting and promising research-oriented activities related to robotic capsule endoscopy, such as i) locomotion and localization methodologies for endoscopic capsules, ii) mesoscale mechanisms for diagnosis and therapy delivery, iii) image-based algorithm for enhanced diagnosis, etc. During the workshop the contributions will be discussed by the authors in a poster teaser session and during a dedicated poster session.

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Vision/Inertial-Based Image Mapping for Capsule Endoscopy

Yasmeen Abu-Kheil, Marco Mura, Gastone Ciuti, Paolo Dario, Lakmal Seneviratne and Jorge Dias

***Abstract*—In this paper, we propose a method for mapping images from a capsule-based endoscope in a way that is more informative to physicians: the technique uses visual and inertial-based data fusion to obtain a 3D map of the lumen from 2D capsule images, also paving the way for the implementation of a path planning and autonomous locomotion and inspection.**

I. Introduction

Capsule Endoscopy is a non-invasive procedure for gastrointestinal (GI) diagnosis. It does not require sedation and it is comfortable and well tolerated by patient. However, the problem with such procedure is that a huge number of images is collected, which require time to investigate and diagnose; furthermore, the capsule movement is not controlled leading, in some cases, to inaccurate diagnosis. In this context, a mapping of the lumen is required to guarantee a higher reliability of the inspection, enabling the medical doctor to evaluate all the parts of the lumen for a better diagnosis. In this paper, image and 3D motion flow based algorithms [1] are used to extract useful image features and information for image mapping and surface reconstruction. Then, a set of measured optical flow features between two selected images were fused with motion parameters obtained from Inertial Measurements Unit (IMU) to generate a map of the GI tract.

II. 3D Mapping Architecture

The general capsule locomotion platform and mapping architecture is shown in Fig. 1. The overall system will consist of a six degrees of freedom robotic arm equipped with an external permanent magnet (EPM), a capsule device that includes an internal permanent magnet (IPM) that interacts with the external magnet as well as mapping algorithm. The movement of the capsule is guaranteed by the magnetic field interaction between the EPM, attached to the robotic arm, and the IPM, integrated inside the capsule [2]. The mapping algorithm consists of three main modules: i) the vision module, ii) the inertial module and iii) the fusion module. Then, the mapping algorithm outputs (i.e., acquired images, linear accelerations and angular velocities) will be sent to a remote computer where they are fused and processed. The mapping algorithm computes the optical flow features from the acquired image sequence and then uses a non-linear Kalman filter algorithms to estimate the translational optical flow from the measured angular velocities and the computed optical flow. The translational optical flow can provide the depth and map sequence; processed information will be also fed back to the robotic arm for control aspects.

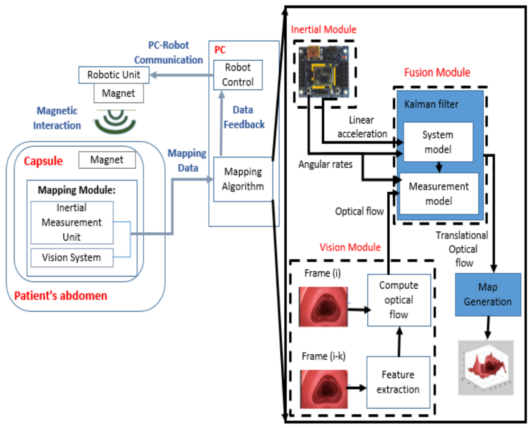

Figure 1. Overall system architecture

III. Experimental Results

Preliminary experiments on images taken from an in-vitro colon simulator were conducted. The proposed algorithm was applied to two different sets of motion: translational and rotational motions of the capsule, obtained with the robotic arm. Results showed that visual and inertial-based techniques achieved promising performance in 3D mapping. A sample map is shown in Fig.1 after map generation block. The map present a consistent, even if qualitative, estimation of the colon simulator structure.

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Wireless Capsule Endoscope Tracking based on Multiscale Elastic Image Registration

Isabel N. Figueiredo, Carlos Leal, Luís Pinto, Pedro N. Figueiredo, and Richard Tsai

***Abstract*— We propose a multiscale elastic image registration incorporating an affine pre-registration for wireless capsule endoscope (WCE) imaging motion. 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 gastrointestinal peristaltic movement. Under this approach a qualitative information about the WCE speed can be obtained. Moreover by using projective geometry, the scale and rotation parameters resulting from the registration scheme, can be related to the capsule orientation and displacement.**

I. Introduction

WCE is an imaging technique that permits physicians to examine all the areas of the gastrointestinal tract, and in particular the small intestine which is an organ that is not easily reached by conventional endoscopic techniques. However, the WCE precise location in the human body during its operating time is not know. Therefore, when an abnormality is detected, in the WCE images, medical doctors do not know precisely where this abnormality is located relative to the intestine and therefore they can not proceed efficiently with the appropriate therapy. As the WCE is propelled by peristalsis, the motion of the walls of the small intestine, in consecutive frames, is a consequence of a combination of two types of movements [2] that are interconnected: the WCE movement, which is rigid-like, and the non-rigid movement of the small intestine (that is an elastic organ that bends and deforms as a consequence of the peristaltic movement). We propose a new procedure [1], for tracking the WCE motion, that takes into account the combination of the two aforementioned movements.

II. Proposed Approach

In a first step a parametric pre-registration is performed at a coarse scale, and gives the motion that corresponds to an affine alignment of two consecutive images, thus matching the most prominent and large features, and correcting the main distortions, originated by the WCE movement. In the second step, and based on the result of the first step, a multiscale elastic registration is accomplished. This second step corrects the fine and local misalignments generated by the non-rigid movement of the gastrointestinal tract. Moreover we further enhance the quality of this approach by iterating it twice.

III. Results

The results of the tests evidence a better performance of the multiscale elastic image registration compared to the multiscale parametric image registration, to the real objective of WCE localization and orientation, when elastic deformations are involved (which is the realistic scenario since the capsule motion is driven by peristalsis). The multiscale parametric image registration is similar to other existing approaches [3], that essentially rely on affine correspondences between consecutive frames, and consequently are only capable of capturing rigid-like movements.

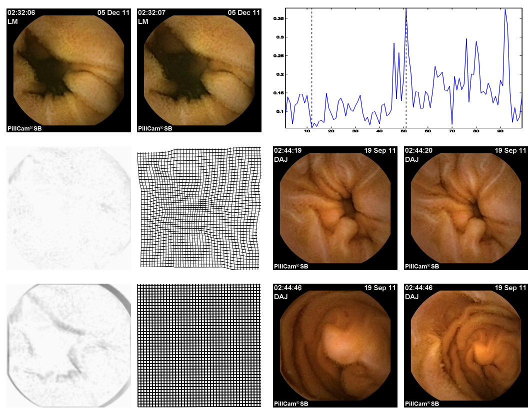

Figure 1. Columns 1-2 (from left to right): original template T and reference R (top); difference between registered T and R, and deformed grid obtained with the proposed approach (middle) and with the multiscale parametric image registration (bottom). Columns 3-4: qualitative speed estimation of the capsule for a WCE video with 100 frames (top); consecutive frames T and R, in the WCE video, with the biggest (middle) and lowest (bottom) similarity (left and right dashed vertical lines in the top subfigure).

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Towards a Color Space for Automated Lesion Segmentation in Robotic Capsule Endoscopy

Spiros V. Georgakopoulos, Panos Chrysanthopoulos, Dimitris Chatzis, Anastasios Koulaouzidis, Vassilis P. Plagianakos, *Member IEEE*, and Dimitris K. Iakovidis, *Senior Member, IEEE*

***Abstract*— Image segmentation plays an important role for the assessment of endoscopy images, e.g., for lesion recognition and measurement. This paper presents a method for superpixel-based segmentation of various gastrointestinal lesions using a novel color space constructed by Kernel Principal Component Analysis. The advantageous results obtained with a publicly available dataset are promising for the development of future robotic capsule endoscopy systems with enhanced diagnostic capabilities.**

I. Introduction

Passive wireless capsule endoscopes (WCE) are evolving into active robotic devices with capabilities for locomotion, and enhanced diagnostics [1]. In this context, image segmentation is important for automated lesion recognition and size measurement [2]. A pioneering approach for color image segmentation was based on principal component analysis (PCA) [3]. In the latter, the red, green and blue components of the RGB color space are linearly transformed into three décorrelated components forming the $I_1I_2I_3$ color space. These components are ordered by their variance, i.e., I_1 represents the component with the highest variance and corresponds to luminance, with I_2 and I_3 represent lower variance components. In a later study [4], an improved performance over PCA for color space construction was indicated with the use of independent component analysis (ICA). However, this was only qualitatively assessed, whereas ICA has the drawback of being dependent on initialization. In WCE, PCA has been utilized only for segmentation of reddish lesions [5]. Image segmentation was based on thresholding schemes. In this paper, a novel method for segmentation of various lesions (not only reddish) is proposed. It is based on non-linear kernel PCA for the color space construction and a modified simple linear iterative clustering (SLIC) superpixel segmentation [6].

II. Methodology

Each RGB channel of a given image is represented as a vector. The three vectors obtained, form a data matrix X_{3xn}. A kernel matrix $K_{ij} = k(X_i, X_j)$ is applied on each RGB pixel of the dataset X_i, $i=1,...,n$, where k is the kernel function. Subsequently, the eigenvectors of K (that correspond to the matrix transformation) are calculated. Each eigenvector component contributes to the linear transformation from the RGB color space to the new one, called $K_1K_2K_3$. The RGB to $K_1K_2K_3$ transformation matrix is obtained by

$$M = \begin{bmatrix} 0.77773 & -0.17356 & -0.60417 \\ 0.24861 & -0.79784 & 0.54923 \\ -0.57735 & -0.57735 & -0.57735 \end{bmatrix}$$

Subsequently, Welch's *t*-test is utilized to capture the most discriminative chromatic components. A modified SLIC superpixel segmentation algorithm is applied for WCE image segmentation, where only K_2 and K_3 are used for the estimation of color distances instead of all the CIE-Lab components considered in the original algorithm.

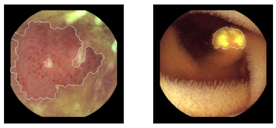

Figure 1. Indicative segmentation results of an aphthae (left) and a lymphanigiectasia (right).

III. Results

We used the dataset described in [7] for the segmentation of angioectasias, polypoid lesions, lymphangiectasias, stenoses, ulcers, aphthae, and chylous cysts. This dataset includes also normal images and images with intestinal content. It is publicly available via the KID database [2]. A 40% sample of these images was used to apply KPCA using third order polynomial kernel function. The rest, non-overlapping, samples were used for testing. The average performance of the proposed method was higher (94%) than the one obtained by using CIE-Lab (92%). Indicative results are illustrated in Fig. 1.

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Quantitative performance analysis of endoscopic procedures: a novel image-based methodology

Menat Alla Saleh, Marco Mura, Yasmeen Abu-Kheil, Kinda Khalaf, Gastone Ciuti, Paolo Dario, Lakmal Seneviratne and Jorge Dias

***Abstract* - This paper proposes a software tool that aims to evaluate the precision of the traditional endoscopic procedure as well as the endoscopists' performances.**

I. Introduction

Colorectal cancer has the third highest incidence of cancers among men, and the second among women worldwide. More than 1 million cases are diagnosed annually [1]. Screening methods like colonoscopy and video capsule optical imaging are the main procedures in which colorectal cancer can be detected along with other diseases. They provide early diagnosis, which helps in decreasing the mortality rate of colorectal cancer, which was reported to exceed 500.000 deaths worldwide in 2012 [1]. However, these screening methods have a high miss rate that may allow other anomalies, such as lesions or polyps, to go undetected leading to a false negative results. Consequently, an evaluation of the procedure is required to guarantee a higher reliability of inspection, enabling the medical doctors to evaluate the procedure and the endoscopists' performance for an accurate diagnosis.

In this paper, we propose a software tool that automatically assesses the procedure to allow accurate and reliable diagnosis.

II. Methodology

The proposed technique utilizes images collected from the endoscopy video and analyzes them in terms of four specific metrics as a standard in which the evaluation can be based on. These metrics are: i) endoscopic velocity profile: observe how different velocities of the endoscope can affect the quality of the image collection, and consequently, the quality of the endoscopy procedure; ii) blurriness of the images: identify and remove blurry images and explore the affect it has over the quality of inspection of the colon and the overall quality of the endoscopy procedure; iii) areas of specularity: observe how high specular areas limit the inspection by not giving an appropriate feedback which affects the overall quality of the procedure; iv) level of bowel preparation: identify areas covered by stool in order to evaluate the level of bowel preparation. The software then removes the images that are uninformative based on the metrics to obtain a clean dataset. From this clean dataset of images, a 3D reconstruction is built to reveal the areas that are not properly inspected. Hence, a percentage of the overall covered area can be calculated. From the 3D reconstruction and image analysis, online and offline informative feedback is given to indicate which areas are inspected properly, and which areas lack good examination. Figure 1 shows the general architecture of the system and the algorithm in which the software tool operates.

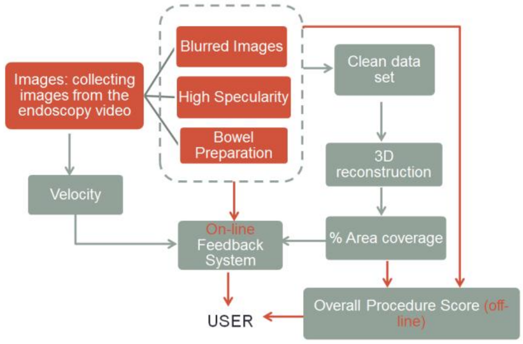

Figure 1: The system architecture

The online feedback will be in the form of an alert to the user during the procedure, and the offline feedback will be in a form of an overall score given after the procedure is complete. Our tool will be integrated into three screening systems: i) passive capsule, giving an offline feedback; ii) active capsule; and iii) endoscopic standard procedure in which it can give an on-line and off-line feedback for both.

III. Results and Future Work

In-vitro and *ex-vivo* tests were performed to collect images from the endoscopic video for two purposes: i) test the tool in detecting the uninformative images; and ii) set threshold values, which images are evaluated based on each metric with the help of a medical doctors. The direction of future work includes the assessment of the entire tool and algorithm by expert medical doctors.

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Mechanical Mechanism and Principles for Active Capsule Locomotion

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***Abstract*— In recent years, wireless capsule endoscopes have been used for diagnosis of the digestive intestinal tract in spite of their disadvantages of low diagnostic effectiveness and passive locomotion. So, they were restrictively used in small tubular digestive organs, such as small intestine and esophagus. To face these difficulties, researchers have begun studying an active locomotive intestine capsule endoscope as a medical instrument for the whole gastrointestinal (GI) tract. We have developed a capsule endoscope with a small permanent magnet which is actuated by an electromagnetic actuation system (EMA), allowing active and flexible movement in the patient's gut environment. In addition, we have also developed a micro-biopsy module installed in the active locomotive intestine capsule endoscope (ALICE).**

I. Capsule Endoscopy and ALICE for Locomotion

Owing to the limitations of the conventional flexible endoscopes used in gastrointestinal diagnostic procedures, which cause discomfort and pain in patients, a wireless capsule endoscope has been developed and commercialized. Despite the many advantages of the wireless capsule endoscope, its restricted mobility has limited the use to diagnosis of the esophagus and small intestine only [1, 2, 3]. Therefore, to extend the diagnostic range of the wireless capsule endoscope into stomach and colon, an additional mobility of the capsule endoscope is necessary.

We proposed a novel electromagnetic actuation (EMA) system that can realize a three dimensional (3-D) locomotion and a steering within the digestive organs. The proposed active locomotion intestinal capsule endoscope (ALICE) consists of five pairs of solenoid components and a capsule endoscope with a permanent magnet. With the magnetic field generated by the five pairs of solenoid components, the capsule endoscope can perform various movements necessary to the diagnosis of the gastrointestinal tract, such as propulsion in any direction, steering, and helical motion.

From the results of a basic locomotion test, ALICE showed a propulsion angle error of less than 4° and a propulsion force of 70 mN. To further validate the feasibility of ALICE as a diagnostic tool, we executed ex-vivo testing using small intestine extracted from a cow. Through the basic mobility test and the ex-vivo test, we could verify ALICE's usability as a medical capsule endoscopic system.

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II. Biopsy Module: for More Accurate Diagnosis

In addition, researchers have noted the need for a biopsy function in a capsule endoscope for the histological examination of digestive diseases. Therefore, we proposed a novel robotic biopsy module for ALICE. The proposed biopsy module has a sharp blade connected with a shape memory alloy actuator. The biopsy module with 12mm in diameter and 3mm in length was integrated into our ALICE prototype, where the module's sharp blade was activated and exposed by the shape memory alloy actuator.

Then the EMA system could generate a specific motion of the ALICE prototype to extract a tissue sample from the intestinal walls. Through an in-vitro test, the sampled biopsy tissue had a volume of about $6mm^3$, which is a sufficient amount for a histological analysis. Consequently, we proposed the working principle of the biopsy module and conducted the in-vitro biopsy test to verify the feasibility of the biopsy module integrated into the ALICE prototype using the EMA system.

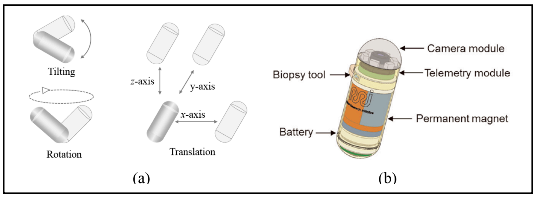

Figure 1. (a) 5 motion of ALICE, and (b) ALICE with biopsy module

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A Combined Structured Light and Photometric Stereo Endoscope for Dynamic Tissue Measurement

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***Abstract*— *In situ* 3D reconstruction from endoscopic images is important to determine the correct course of action for, e.g., treatment of abnormal growths. Currently, the endoscopist has to rely solely on visual cues in order to infer the growth's shape and size and determine an appropriate treatment. We present a custom single-fiber structured light probe projecting a wave pattern on the tissue surface that allows semi-dense reconstruction with few ambiguities. Based on the coarse reconstruction, we initialise a close-range Photometric Stereo module which provides dense metric 3D shape information. A preliminary study was carried out both on phantoms and *ex vivo* samples of human tissue.**

I. Outline

In this work, we contribute by proposing a Structured Light (SL) endoscope with an integrated projector in its instrument channel. We improve the Photometric Stereo (PS) formulation for endoscopes by using the SL reconstruction to initialise a novel non-Lambertian PS technique that is independent of the surface albedo and explicitly takes into account light intensity distribution and position. Importantly, our system does not require significant alterations to standard equipment. To the best of our knowledge, this is the first work combining structured light and photometric stereo applied to endoscopy. Our proposed system consists of two main modules: first, we miniaturised a laser pattern projector consisting of a single optical fiber that is fed through the instrument channel of the endoscope for SL projection. Second, the PS module consists of three externally mounted LEDs. While our prototype does not satisfy the endoscope size requirements due to the external mount, in the final product stage it will be possible to include three internal LEDs, or to apply colour filters to the on-board lighting. The overall system with the projected lights and patterns is shown in Fig. 1. For its operation, we first obtain a sparse SL reconstruction by pattern matching of the projected wave pattern according to the method in [1]. The reconstructed elements are used as seeds for the PS method proposed in [2], which allows to propagate the reconstruction to the remaining unknown points irrespective of the albedo and taking into account light attenuation, yielding a dense 3D reconstruction in absolute metric coordinates. Details of the method can be found in [3].

Figure 1. Left: Close-up of the scope head, with three LEDs for PS and green laser SL probe. Right: Projected PS lights and SL pattern.

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II. Results

We tested the performance of our SL module on an anatomical phantom model, while the complete system was tested on *ex vivo* tumour samples. In Fig. 2 images of the phantom as well as the tumours are shown under SL and PS illumination, followed by renderings of their 3D reconstructions. The method runs in around 400ms on a standard desktop PC, and the method is able to densely reconstruct the general surface trend of the target object. Finally, the actual distance of the target objects was manually measured and found to be within 5mm of its reconstructed value, thus indicating a promising result for future intraoperative assessment of tumour sizes.

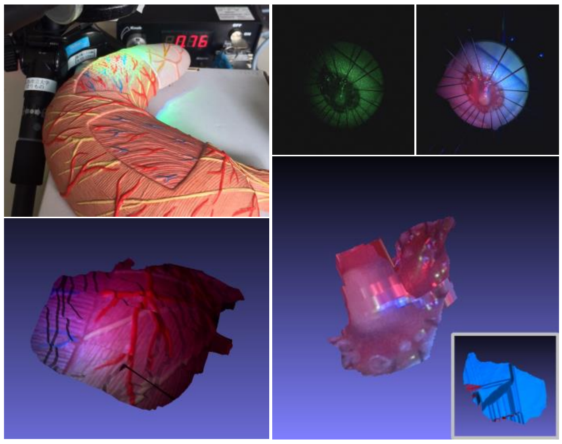

Figure 2. Reconstruction renderings of phantom and *ex vivo* tumour.

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