AC 2011-644: A CASE STUDY ON PILL-SIZED ROBOT IN GASTRO-INTESTINAL TRACT TO TEACH ROBOT PROGRAMMING AND NAVIGATION

Yi Guo, Stevens Institute of Technology

Yi Guo received the B.Sc. and M.Sc. degrees in Electrical Engineering from Xi'an University of Technology, China, in 1992 and 1995, respectively. She obtained the Ph.D. degree from the University of Sydney, Australia, in 1999. From 2000 to 2002, she was a postdoctoral research fellow at Oak Ridge National Laboratory. She was a Visiting Assistant Professor at University of Central Florida from 2002 to 2005. Since 2005, she has been an Assistant Professor in the Department of Electrical and Computer Engineering at Stevens Institute of Technology. Her main research interests are nonlinear control systems, autonomous mobile robots, reconfigurable sensor networks, and control of nanoscale systems. Dr. Guo is a Senior Member of IEEE.

Shubo Zhang, Stevens Institute of Technology

Shubo Zhang received the B.S. degree from department of Automatic Control at Beijing Institute of Technology, Beijing,China, in 2007 ,and the M.E. degree in Electrical Engineering from Stevens Institute of Technology, Hoboken, NJ, USA , in 2009. He is currently working toward the Ph.D. degree in the Department of Electrical and Computer Engineering, Stevens Institute of Technology. His research interest is control design for Micro/Nano-robots in Biomedical Applications.

Hong Man, Stevens Institute of Technology

Dr. Hong Man joined the faculty of Electrical and Computer Engineering at Stevens in January 2000. He received his Ph.D. degree in Electrical Engineering from the Georgia Institute of Technology in December 1999. Dr. Man is currently an associate professor in the department of ECE. He is serving as the director of the undergraduate Computer Engineering program, and the director of the Visual Information Environment Laboratory at Stevens. His research interests have been in image and video processing, medical imaging, data analysis and pattern recognition. He has authored or co-authored more than 60 technical journal and conference papers on these topics. He is a senior member of IEEE and member of ASEE.

Arthur B. Ritter, Ph.D., FAIMBE, Stevens Institute of Technology

Dr. Ritter received his BChE degree from the City College of New York, and his MS and PhD degrees in ChE from the University of Rochester. Before returning for his PhD degree he had over 10 years of industrial experience in the aerospace industry for the US Navy and United Aircraft in solid rocket propellant development and as a development engineer for the Mixing Equipment Company and the DuPont Co. His first academic appointment was at Stevens Institute of Technology in the department of Chemistry and Chemical Engineering where he did research on solar energy storage and conversion and optimal control of chemical processes. He taught courses in transport phenomena and process control. While at Stevens he met Francis Chinard, MD from UMD-New Jersey Medical School and started collaborative research in pulmonary transport and metabolism in-vivo. This led to a full time position in Dr. Chinard's lab in the department of Medicine at NJMS. After a few years he was recruited to the department of Physiology where he spent the next 20 years teaching Cardiovascular and Respiratory physiology, statistics for the life sciences and physical chemistry to Medical, Dental and Graduate students. His research areas were microcirculatory and cardio-respiratory physiology. He was course director of the medical physiology course for 5 years before returning to Stevens to start the Biomedical Engineering program. He was the PI or Co-PI on grants from NSF, NIH, AHA and New Jersey Commission on Science and Technology. Dr. Ritter has mentored 9 PhD students in Physiology and Biomedical Engineering and over 40 Masters student's in Biomedical Engineering. He is the co-author of over 45 publications in peer reviewed journals and numerous abstracts and presentations at local, national and international conferences. He is the primary author of an undergraduate textbook in Biomedical Engineering. His current research interests are in Systems Physiology, Rotary Protein Motors, The Failing Heart, and Biorobotics. He recently started a Biorobotics lab for research in Robotics and minimalyy invasive surgery with colaboration with surgeons at Hackensack University Medical Center (NJ).

A Case Study on Pill-Sized Robot in Gastro-Intestinal Tract to Teach Robot Programming and Navigation

Abstract

We present instructional materials to teach bio-medical engineering students about the design and control of a capsule robot operating in the human's GI tract. A design example to conceptually build such a micro-robot is first presented, and a laboratory module is then developed to demonstrate robot navigation techniques. Medical considerations such as size, speed, safety, and functionality of the robot are discussed, and robot building components including sensors, actuators, processing, communicating, and power supply are provided. The laboratory module is built on the 3D Webots simulation platform. Path planning, collision avoidance, and other robot navigation methods are introduced to acquaint bio-medical engineering students with modern robotic control techniques.

Introduction

Micro/nano-robots for biomedical applications are an emerging area that has received advancement during the last decade. Though books/textbooks exist in nanotechnology, there are a growing number of articles appearing in journals and conference proceedings in biomedical micro/nano-robotics. Medical robotics has been an active research area since the 80s and an enormous amount of teaching materials is available, particularly in medical instrumentation and medical imaging. Contrary to the large amount of teaching and learning materials on large-scale medical robots, instructional materials on micro/nano-robotics for bio-medical applications are very limited. There is a general lack of learning materials on micro/nano-robotics in undergraduate education. We have developed teaching materials targeting undergraduate students in bio-medical engineering and related disciplines where micro-robotics techniques could be readily applied.

In this paper, we present a case study on a pill-sized robot in gastro-intestinal (GI) tract to teach undergraduate micro-robotics and also principles of robot programming and navigation. The case study consists of a design example and a laboratory module. The design example proposes a conceptual design of a vitamin pill size robot vehicle that can operate within the human's GI tract. The laboratory module is based on the platform of the Webots simulator. The objective of the laboratory modules is to teach students how to program robots to navigate in an uncertain environment and how to control the robot. Two main robot navigation mechanisms will be demonstrated: the semi-autonomous and autonomous modes. In the semi-autonomous mode, humans can interfere with or control the robot through communication when needed; while in the autonomous mode, the robot is pre-programmed so that it achieves the task and adapts itself to the environment intelligently.

Design Example of Pill-Sized Robot

Design Principles

Medical considerations provide design requirements for capsule robots such as size, speed, safety and functionality. The proposed capsule robot aims to effectively visualize the GI tract with navigation and tracking capability. The design principle of the capsule robot needs to consider both medical constraints and application scenarios.

Size: Since the size of the capsule is very important (very large pills make patients uncomfortable), the designed capsule must be sufficiently small to be swallowable. This limitation dramatically increases design difficulties. The trade-off between size and capabilities must be taken into consideration. The foremost challenging is miniaturization to obtain an ingestible device. In order to be swallowable, a capsule robot could fit within a cylindrical shape 9 mm in diameter and 23 mm long--the size of commercial pill-cameras such as the capsule Sayaka[1], is the smallest endoscopy capsule.

Speed: A standard colonoscopy is completed in approximately 20 min-1 hour[2], so it is desirable for a locomoting robot to be able to move fast enough to travel through the colon in this time. While a fast response time would be preferable, it is impossible to immoderately increase speed because of the dissipation of power and patients' safety.

Safety: When operating within the human body, safety must be taken as the most important concern. The capsule's contact with the walls of the GI tract should cause no more damage than a standard colonoscope. The design of capsule must be considered with safety and biocompatibility.

Functionality: Some of the early concepts are now on the market. Families of sensing capsules provide temperature[3,4], pressure[3], imaging[5,1,3,6], pH data[3], drug delivery[6], tissue sampling[3], and polyps detection[7] to complement classic diagnostics, and one capsule delivers medication. There are also some potential applications, such as obscure bleeding, diagnostic pancreatic cancer, esophageal cancer and gastric cancer. It is desirable to design a capsule robot that could combine the above functionalities and locomotion capabilities.

Application Scenarios

The proposed capsule is a self-contained micro-system that can perform sensing and actuating function in the GI tract. Sensing function includes temperature, pressure, imaging, pH data and tissue biopsy. Actuating function is that the capsule robot has the ability to move in 2-dimensions, moving forward and turning, which enables it to implement tracking in the stomach. Since it is not economical to consider a medical doctor waiting all the time during the all endoscopy process which can take around 5-20[8] hours, the following scenario is proposed for the application of the robotic endoscopic capsule. At first, the capsule robot (with the tracking mode) is swallowed by the patient with the standard out of hospital process and gets a map and approximate position of all GI tract regions with potential problems. In tracking mode, the capsule robot could finish the GI tract faster than the standard commercial capsule camera. Next, the robotic capsule (with navigation mode) is swallowed by the patient. The capsule could be activated and controlled by a clinician to anchor itself in the desired place that needed to conduct a detailed temperature, imaging, pressure, pH data and tissue biopsy. Locomotion capability of the capsule robot will allow the clinician to adjust the forward and turning position of the capsule. These operations could be also realized remotely by the doctor through wireless internet.

Conceptual Design

Actuators: As outlined above, the actuator must be safe to use inside the human body. It would be preferable that the actuator has large strain capability, produces high output force, draws low power, and is small in size.

The selection of the actuators has been discussed[9]. Piezoelectric materials were considered for their small size, high output force, quick speed, and low power consumption. However, the need for a high driving voltage raises questions as to its biocompatibility. Combined with its small strain capability, this was determined to be reasonable cause to look at other actuators.

Polymer actuators have become increasingly popular in robotics. The large strain capability and its biocompatibility are attractive. Unfortunately, these actuators are slow, relatively bulky, incapable of high output force, and consume large amounts of power.

The next actuator considered was shape memory alloy (SMA). This type of actuator had all the qualities necessary for this device with two exceptions. SMA is heat-activated and thus has very low efficiency and slow response time. In addition, this means that the device dissipates a lot of power. Despite this drawback, it was decided that SMA would be sufficient for the purposes of a capsule prototype. The issue of power consumption will be addressed as the project progresses further.

Our conceptual design of the capsule robot is inspired from the earthworm-like locomotive mechanisms proposed by Kim *et al.*[10]. In order to realize a 2-dimensional locomotive mechanism, four spring-type SMA actuators are required to have long stroke and a strong enough force to overcome resistance force due to deformation of small intestine. The developed actuator is integrated with clampers mimicking claws of insects and an earthworm-like locomotive mechanism is proposed. The SMA actuators can be controlled to contract and stretch by passing current through the wire. When all four SMA are actuated in the same rhythm, the capsule robot moves forward or backward. Turning capability can be achieved by actuating the left and right SMAs in the opposite rhythm. Based on the design of actuators, the capsule robot have the ability to move in 2-dimensional, moving forward and turning, which enables it to implement tracking and navigation in the GI tract.

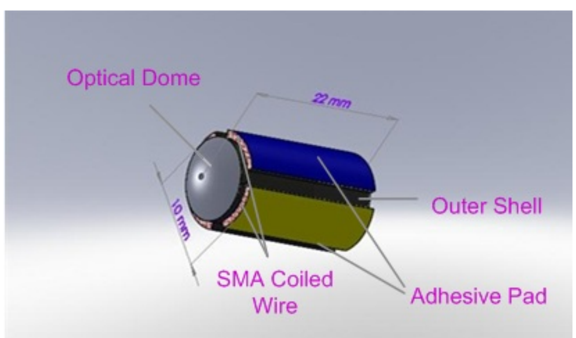

Figure 1. The endoscope capsule robot.

The capsule robot measures 10 mm in diameter and 22 mm in length, see Figure 1. The outer shell of the device is biocompatible material. The SMA coiled wire is attached to an adhesive pad. An optical dome is embedded in the front of the capsule. An inner shell contains five modules: vision module, sensors module, communication module, CPU module and battery.

Vision Module: Unlike PillCam, which uses CMOS (complementary metal-oxide semiconductor) image sensors, this device uses a CCD (charge-coupled device) image sensor. This results in superior image quality but with much greater power consumption due to the intense digital signal processing involved. The CCD image sensor is compassed by four illumination light emitting diodes (LEDs) with different wavelengths.

Sensors Module: Sensors convert physical properties such as light, pressure, or temperature into electrical signals. The capsule robot embedded sensors, including temperature, pressure and pH data.

Communication Module: The communication module can then both transmit and receive the signal to communicate with outside the console. The RF antenna is utilized to receive external operation signal, such as activation, motion commands and switch operation modes. Transmitter block sends the data, which is gathered from the sensors module, to the outside console .

CPU Module: The system's brain, the CPU, on one hand, digitizes the signals which are provided by the sensors and vision modules. On the other hand, the CPU performs additional processing of execution commands, which operates the SMA actuators in control principle.

Power Supply: The capsule robot is powered by silver oxide batteries, which can provide over 5 hours of continuous video recording. In battery-powered devices, the battery itself is likely the largest system component. Therefore, designers must minimize both supply voltage and current consumption while using high-efficiency topologies to achieve the required system performance.

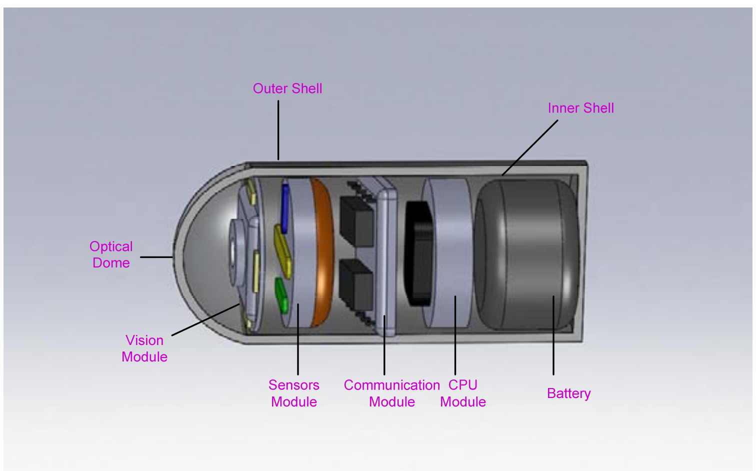

Figure 2. Inside of the endoscope capsule robot.

As a conceptual design, one-third of the capsule will house the power supply and propulsion system, one third will house the electronics including guidance, data transmission and control, and one third will house the hardware associated with sensing capabilities such as imaging, see Figure 2.

<u>*Navigation and Control Design*</u>

In the case of a capsule endoscope robot, the specific aspect of cognition directly linked to robust mobility is *navigation competence*. Given partial knowledge about its environment and a goal position or series of positions, navigation encompasses the ability of the robot to act based on its knowledge and sensor values so as to reach its goal positions as efficiently and as reliably as possible.

First we discuss two key additional competences required for capsule endoscope robot navigation. Given a map and a goal location, *path planning* involves identifying a trajectory that will cause the robot to reach the goal location when executed. *Path planning* is a strategic problem-solving competence, as the robot must decide what to do over the long term to achieve its goals.

The second competence is equally important but occupies the opposite, tactical extreme. Give real-time sensor reading, *obstacle avoidance* means modulating the trajectory of the robot in order to avoid collisions.

Path planning overview[11]: The robot's environment representation can range from a continuous geometric description to a decomposition-based geometric map or even a topological map. The first step of any path planning system is to transform this possibly continuous environmental model into a discrete map suitable for the chosen path planning algorithm. Path planners differ as to how they affect this discrete decomposition. We can identify three general strategies for decomposition:

1. Road map: identify a set of routes within the free space.

2. Cell decomposition: discriminate between free and occupied cells.

3. Potential field: impose a mathematical function over the space.

Path planning: For the GI tract example, we use potential field strategy for path planning. The potential field method treats the robot as a point under the influence of an artificial potential field U(q). The robot moves by following the field, just as a ball would roll downhill. The goal acts as an attractive force on the robot and the obstacles act as repulsive forces. The superposition of all forces is applied to the robot, which, in most cases, is assumed to be a point in the configuration space. Such an artificial potential field smoothly guides the robot toward the goal while simultaneously avoiding known obstacles. The basic idea behind this method is that the robot is attracted toward the goal, while being repulsed by the obstacles that are known in advance.

The capsule could traverse the whole GI tract by implementing the above algorithm. But in this scenario, we only take into consideration the environment obstacles that are known to the capsule in advance. During path execution the robot's actual sensor values may disagree with expected values due to map inaccuracy or dynamic environment. Environment dynamics become more significant, making the path planning techniques described above become inadequate for grappling with the full scope of the problem. Therefore, it is critical that the capsule modify its path real time based on actual sensor values. This is the competence of obstacle avoidance which we discuss below.

Obstacle avoidance: It is the behavior to avoid potential collisions with obstacles in the environment. If the front sensor detects obstacles in front of the robot, the robot avoids the detected obstacle by circumnavigating it.

For the GI tract example, the data rate can be dynamically adjusted by the following events: 1) change of sections in the gastrointestinal tract (GI tract) (esophagus, stomach, small intestine, large intestine), 2) detection of tissue anomaly, 3) upon request by the physician. Taking into account the aforementioned events, we propose that the capsule endoscope robot can operate in two working modes: tracking mode and navigation mode.

Tracking Mode: Tracking mode is that the capsule endoscope robot is operated with the behavior of following the wall in the GI tract. In the tracking mode, the capsule robot could get a map and approximate position of all track regions with potential problems without being supervised. Most of the time, the capsule robot utilizes the forward gait with a constant speed. When some predefined events occur, we may adjust the speed. For instance, when the sensors detect a dramatic change data rate, the capsule robot will decrease the speed or anchor to get more information.

Navigation Mode: In the navigation mode, the capsule could be activated and controlled by a clinician to anchor itself in the desired place to conduct a detailed temperature, imaging, pressure, pH data and tissue biopsy. Locomotion capability of the capsule robot will allow the clinician to adjust the forward and turning position of the capsule. These operations can be also realized remotely by the doctor through the internet.

Laboratory Module to Simulate Pill-Sized Robot in GI Tract

The process of an ingested capsule communicating wirelessly with an external control console is shown in Figure 3. The capsule is swallowed by the patient and traverses esophagus, stomach, small intestines, and big intestinal. In the tracking mode, the capsule captures the information of the GI tract and transmits the data to the external console through on-board communication module. The external console could get a map and approximate position of whole GI tract regions with potential problems. In the navigation mode, the clinician could drive the capsule robot to the desired places that are needed to acquire more detailed information.

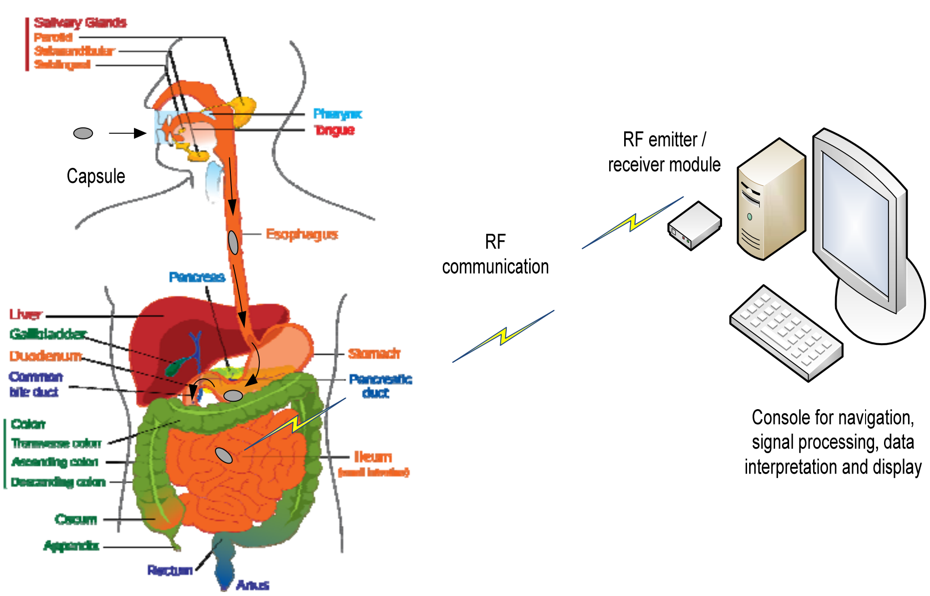

Figure 3. An ingested capsule communicates wirelessly with an external control console.

We built a biomedical environment in Webots simulator to imitate the GI tract. The tracking and navigation operation modes are simulated. For the tracking mode, we simulate a scenario of the capsule passing through the GI tract and getting a map of the whole GI tract, as shown in Figure 4.

The capsule is activated when it reaches the esophagus. The vision module starts to work and gets real-time video sequences, as shown in Figure 4 a. Figure 4 b shows the capsule is approaching the stomach. And Figure 4 c and Figure 4 d show the capsule is tracking in the stomach and small intestines respectively.

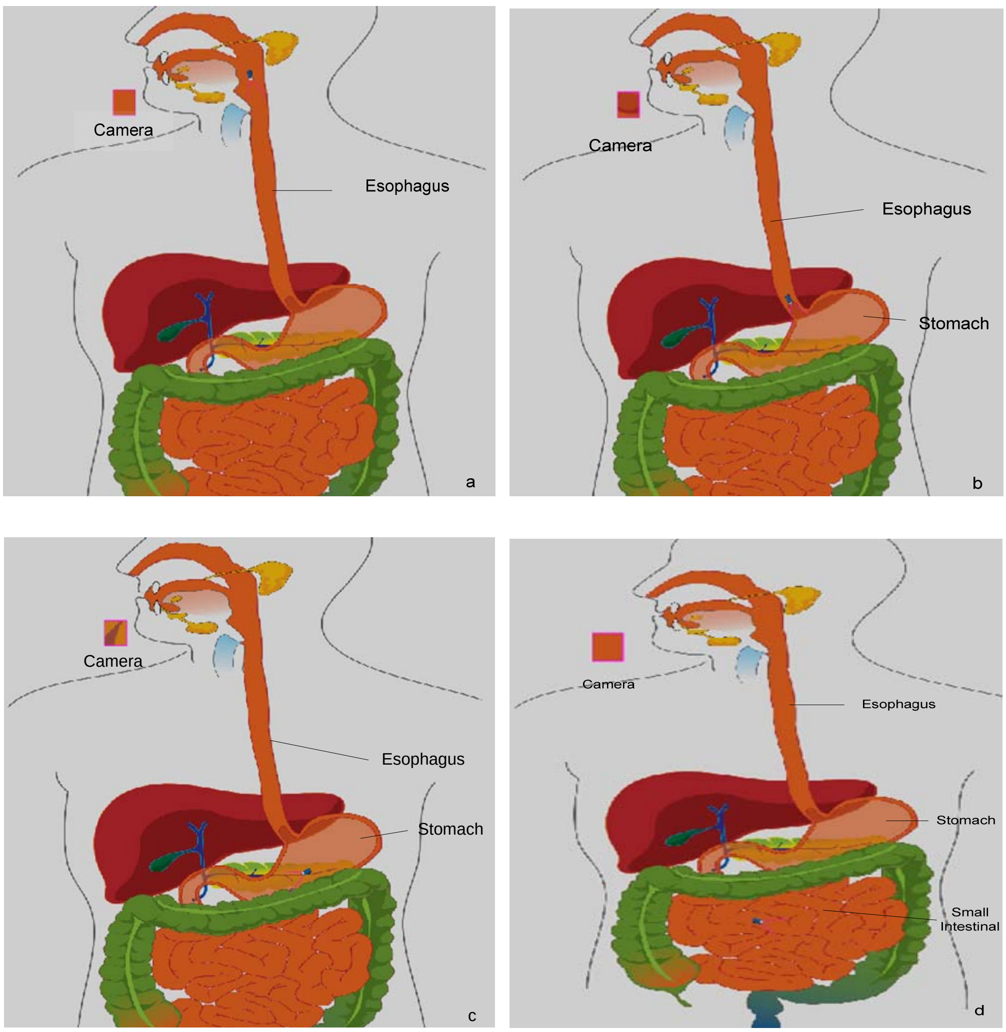

Figure 4. The capsule is operating in the tracking mode.

In the navigation mode, the capsule can operate either in the autonomous mode or remote control mode. For the autonomous mode, the capsule first operates the same procedures as the tracking mode. When the capsule detects the inimical tissue, it will anchor for a while in order to gather more information. Then the capsule resumes tracking mode. In Figure 5, the capsule is operating in the autonomous mode while detecting an inimical tissue.

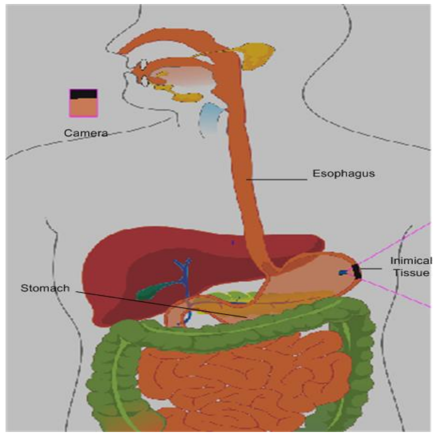

Figure 5. The capsule is operating in the autonomous mode.

After the analysis of the data which is gathered by implementing the autonomous mode, the capsule may operate in the remote control mode by a doctor. The doctor can navigate the capsule to the regions which could have inimical tissues. More detailed information could be gathered through the camera of the capsule and transmitted to the external console. As shown in Figure 6, the capsule is driven to a region which has an inimical tissue through a relatively short path.

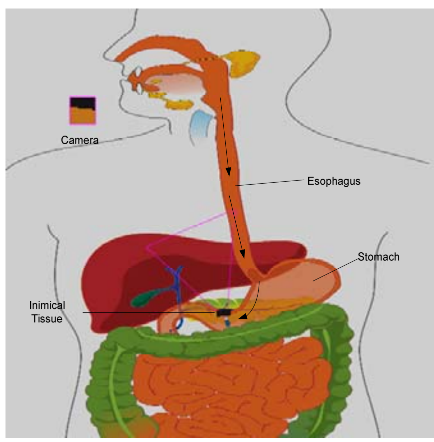

Figure 6. The capsule is operating in the remote control mode.

Conclusion

Wireless capsule endoscopy represents a significant technical breakthrough for the investigation of the GI tract, especially in the light of disadvantages of other conventional techniques. Capsule endoscopy has the potential for use in a wide range of patients with a variety of illnesses. In this paper, we present instructional materials to teach bio-medical engineering students on the design and control of a capsule robot navigating in a human's GI tract. A conceptual design was presented taking into account medical considerations and application scenarios. Navigation and control design was then presented for the capsule robot to track and navigate in the tract. We also developed a laboratory module on the platform of the Webots simulator. Future work includes the implementation of the instructional materials in undergraduate bio-medical engineering courses, and pilot testing.

Acknowledgment

Partial support for this work was provided by the National Science Foundation's Course, Curriculum, and Laboratory Improvement (CCLI) program under Award No. 0837584. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

Bibliography

1. What is "Sayaka", the next generation capsule endoscope? http://www.rfamerica.com/sayaka/index.html, August 2010.
2. Colonoscopy. http://en.wikipedia.org/wiki/Colonoscopy, August 2010.
3. The SmartPill Wireless Motility Capsule. http://www.smartpillcorp.com/index.cfm? pagepath = Products /The_SmartPill_Capsule&id=17814, August 2010.
4. Ingestible Thermometer Pill Helps Athletes Beat the Heat. http://www.nasa.gov/vision/earth/ technologies/thermometer_pill.html, August 2010.
5. Device for In-Vivo Imaging, US Patent 7,009,634, to Given Imaging, Patent and Trademark Office, 2006.
6. I. Wilding, "The Enterion Capsule: A Novel Technology for Understanding the Biopharmaceutical Complexity of New Molecular Entities (NMEs)," Drug Development & Delivery, Vol. 1 No. 1, October 2001.
7. Press Releases. http://www.olympus-europa.com/corporate/presscentre_pressreleases.aspx?area= Medical %20Systems, August 2010.
8. M. Karagozler, E. Cheung, J. Kwon, and M. Sitti. "Miniature endoscopic capsule robot using biomimetic micro-patterned adhesives," IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics, Page(s): 105 - 111, February 2006.
9. P. Glass, M. Sitti, and R. Appasamy, "A New Biomimetic Adhesive for Therapeutic Capsule Endoscope Applications in the Gastrointestinal Tract," Gastrointestinal Endoscopy, Vol. 65, No. 5, Page AB 91, April 2007.
10. B. Kim, S. Park, C. Jee and S. Yoon, "An Earthworm-Like Locomotive Mechanism for capsule endoscopes," IEEE/RSJ International Conference on Intelligent Robots and Systems, Page(s): 2997 - 3002, August 2005.
11. R. Siegwart and I. Nourbakhsh, "Introduction to Autonomous Mobile Robots," The MIT Press, 2004.