A Case Study on a Capsule Robot in the Gastrointestinal Tract to Teach Robot Programming and Navigation

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***Abstract*—Despite the increasing importance of robotics, there is a significant challenge involved in teaching this to undergraduate students in biomedical engineering (BME) and other related disciplines in which robotics techniques could be readily applied. This paper addresses this challenge through the development and pilot testing of a bio-microrobotics case study that can be integrated into curricula in BME, electrical and computer engineering (ECE), and other disciplines. This case study is based on the existing technology of wireless capsule endoscopy and centered on a "grand challenge" of building a capsule robot to navigate the human gastrointestinal tract to detect abnormality or to destroy malignant tissues. First, a conceptual design example for building such a capsule robot is presented, followed by a laboratory module that demonstrates robot navigation techniques using Webots simulation. The case study introduces robotic technologies, including robot building components, operating modes, and behavior-based programming, and students experience robot simulation in the laboratory module. The case study developed was pilot tested in three BME and ECE courses at the authors' institution. The evaluation results demonstrate the effectiveness of the case study in enhancing students' understanding of robotics, interdisciplinary skills, and critical thinking. The case study is shown to support challenge-based learning, which promotes adaptive expertise through rapid knowledge building and innovation.**

***Index Terms*—Behavior-based robot programming, gastrointestinal tract, robot navigation, robot simulation, robotics, Webots, wireless capsule endoscopy.**

I. INTRODUCTION

IT IS predicted that the principle focus in medicine will shift from medical science to medical engineering in future decades, based on techniques derived from the biomedical knowledge gained in the last century [1]. Market demand for professionals with advanced degree training relevant to micro/nanorobotics and nanomedicine will be fueled by the penetration of new discoveries in the field. In this paper, new teaching materials are presented on the navigation of capsule robots in the human gastrointestinal (GI) tract, and results are discussed of pilot-testing the materials in Electrical and Computer Engineering (ECE) and Biomedical Engineering (BME) courses at the authors' institution.

A. National Needs

Over the last decade, there has been a significant growth in the number of undergraduate BME programs and the number of students enrolled in these BME programs. According to the statistics collected by the Whitaker Foundation, undergraduate enrollment has increased from around 5000 in 1993 to over 12 000 in 2003 [2]. The US Bureau of Labor Statistics forecasts that the number of biomedical engineering jobs will climb almost twice as fast as the overall average by 2012. The national growth of BME programs calls for new educational materials supporting biomedical engineering.

Micro/nanorobots for biomedical applications comprise an emerging area that has advanced significantly over the last decade. In addition to books/textbooks in nanotechnology [3]–[5], an increasing number of articles are appearing in journals and conference proceedings in the area of biomedical micro/nanorobotics. However, in contrast to the large amount of teaching and learning materials on large-scale medical robots, instructional materials on micro/nanorobotics are very limited. The proposed case study is intended to bridge this gap and to teach undergraduate microrobotics and its biomedical applications.

B. Institutional Needs

Stevens Institute of Technology, Hoboken, NJ, USA, established a BME program in 2001. In the 2011–2012 academic year, the enrollment consisted of 183 undergraduates and 25 graduates. Currently, BME undergraduate students are taught simulations and feedback control, but encounter no materials on biomedical robotics. During the 2005–2006 academic year, a group of four BME undergraduate students initiated a so-called BioCybernetics project to develop a nanoscale autonomous device in the field of gastrointestinal endoscopy that would have the potential to diagnose, and perhaps treat, illness. The project eventually involved 15 students from mechanical, electrical, chemical, computer, and biomedical engineering, at all levels from freshman to seniors. The students eventually realized that only limited objectives could be met with the resources available and within the time frame of one academic year. Several of the faculty members approached by the students for guidance on various aspects of the project

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recognized a clear need to expand the current curriculum of the BME program at Stevens to include cutting-edge engineering technologies supporting biomedical applications. Had such training been in place, that original group of students would have achieved much more in their BioCybernetics project.

In response to these national and institutional needs, the authors have designed teaching materials based on a microrobot that can be built with the existing technology of wireless capsule endoscopy [6]. These materials include a case study that can be used as a course module in ECE and BME courses. This paper presents the case study developed and the results of pilot-testing it in three ECE and BME courses at Stevens.

C. *Learning Objectives*

The learning objectives of the case study are supported by a conceptual design of capsule robots and a laboratory module. Upon successful completion of the case study, students are expected to have achieved these learning outcomes, so as to be able to do the following:

E1: Understand fundamental science and engineering principles in biorobotics, which include: components of a robot, robot operating modes, design principles of biomedical robots, robot architecture and programming strategies.

E2: Understand the impact of robotics on the health of patients. This includes patient health benefits demonstrated by wireless capsule endoscopy technology, such as noninvasive procedures, less pain, and easy access to the small intestine.

E3: Use computer software (e.g., Webots) in the study and development of biorobotics. This is promoted by the laboratory module developed which allows students to simulate the capsule robot in the GI tract.

E4: Demonstrate interdisciplinary skills in areas such as biomedical design principles, programming, and computer simulation. The engineering disciplines involved include electrical, computer, mechanical, chemical, and biomedical engineering.

II. Grand Challenge

The course materials are centered on the “grand challenge”: to create a semi-autonomous robot that can navigate the human body to detect abnormality or to destroy malignant tissues. The robot is based on existing endoscopic capsule technology such as the PillCam capsule (Given Imaging, Ltd., Yoqneam, Israel) [6], a commercial device the size of a vitamin pill that transmits pictures as it passes through the GI tract, and serves as a replacement for conventional colonoscopy. The PillCam capsule and similar devices are passive, single-function devices. In addition, size, rate of data transmission (bandwidth), and power supply constraints limit its application to the GI tract. The case study starts with the idea of creating a device such as the PillCam capsule, but reducing the size and adding functionality and mobility.

In this section, existing capsule endoscopy technologies are first reviewed, and then the robotic capsule is introduced. It is worth noting that this background knowledge is necessary to achieve the learning outcome *E2*.

A. *Existing Capsule Endoscopy Technologies*

In the US, there are an estimated 19 million people suffering from diseases related to the small intestine, difficult to diagnose through traditional methods such as push enteroscopy, wired endoscopes, and radiology [7]. There are also various inspections for other elements of the digestive system such as the colon and stomach, and it is very difficult for the conventional endoscope to reach the duodenum and small intestine.

Wireless capsule endoscopy has been commercially available since 2001. For the patient, such capsules offer a convenient examination with minimal preparation and immediate recovery [6]. The main vendors are Olympus Optical [8], Given Imaging [9], and the RF System Lab [10]. Given Imaging has developed two distinct capsules: PillCam ESO [11] for the esophagus and PillCam SB [12] for the small bowel, each 11 mm in diameter and 26 mm in length. An external antenna network transfers RF data at the rate of 433.10 MHz and about two to eight frames per second. The on-board silver oxide batteries can provide over 5 h of continuous video recording.

Unlike PillCam, which uses complementary metal-oxide semiconductor (CMOS) image sensors, the Norika3 system by the RF System Lab uses a charge-coupled device (CCD) image sensor, which provides superior image quality. It has much greater power consumption for intense digital signal processing. The capsule is 9 mm in diameter and 23 mm long and has four light emitting diodes (LEDs) each of different wavelengths. The system consists of the capsule, a vest with power transmission coils, a joystick-like device to control the capsule, and a PC system for signal processing, image display, and data storage.

B. *Robotic Capsule Technology*

The commercial wireless capsule endoscopy mentioned above has the advantage of reducing pain and discomfort for the patient due to its wireless nature. However, the capsule moves passively from the mouth to anus under the effects of peristaltic waves and gravity. If a capsule could be activated and controlled by a clinician so as to temporarily resist peristalsis and anchor itself in place in the gastrointestinal tract, additional tools for tissue biopsy, drug delivery, and cleaning or cauterizing angiectasis could be integrated into the device design to enhance its functionality. Since the intestine is an unstructured environment with loose, elastic, slippery walls [13], developing robotic capsules able to move inside the GI tract is more challenging. Nevertheless, recent research has been focused on incorporating locomotion mechanisms into microcapsule robots. There are some capsule robots with an anchoring mechanism that can resist the body’s peristaltic forces to anchor themselves to the intestinal lining at a desired location. Shape memory alloy (SMA) actuators are used in [14] to provide traction, and a later-developed micromotor-actuated locomotion system for capsules was inspired by canoe paddling [15]. Quirini *et al.* [16] have proposed a pill-sized 12-legged endoscopic capsule for locomotion in the lower gastrointestinal tract. Other locomotion methods include a fin-type electromagnetic actuator [17] and a multijoint endocavitary robot actuated by piezoelectric elements [18].

This paper presents a case study on a pill-sized robot in the GI tract. The case study consists of a design example and a laboratory module. The design example proposes a conceptual design of a vitamin pill-sized robot vehicle that can operate within the human's GI tract. The laboratory module is based on the Webots simulator platform. The objective of the laboratory module is to show how to program robots to navigate in an uncertain environment and how to control them. Two main robot navigation mechanisms are demonstrated: the semi-autonomous and autonomous modes. In the semi-autonomous mode, humans can interact with or control the robot through communication when needed, while in the autonomous mode, the robot is preprogrammed to carry out the task and adapt itself to the environment intelligently. In order to achieve autonomous navigation, students first review behavior-based robotic navigation technique, and then create a few behaviors to program the robot navigation functionalities.

The rest of the paper is organized as follows. In Section III, a conceptual design of the pill-sized robot is presented, and its building blocks are introduced. In Section IV, the method to control the microrobot navigating in the human GI tract is discussed. Section V describes the laboratory module built to simulate different robot behaviors based on the Webots robot simulator platform, then evaluation results in three pilot-testing courses are given in Section VI. Finally, the paper is concluded with brief remarks in Section VII.

III. CONCEPTUAL DESIGN OF CAPSULE ROBOT

This section describes the design principles of a capsule endoscopy robot and a conceptual design example, intended to support the expected learning outcome *E1* (Section I-C).

A. Design Principles

Medical considerations dictate certain design requirements for capsule robots such as size, speed, safety, and functionality. The proposed capsule robot aims to visualize the GI tract effectively with navigation and tracking capability. The design criteria for the capsule robot need 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 tradeoff between size and capabilities must be taken into consideration. The foremost challenge is the miniaturization necessary to obtain an ingestible device. In order to be swallowable, a capsule robot must fit within a cylindrical shape 9 mm in diameter and 23 mm long, which is the size of the smallest commercial pill-cameras, such as the capsule Sayaka [10].

Speed: A standard colonoscopy is completed in approximately 20–60 min. A locomoting robot would be expected to move fast enough to travel through the colon in a similar period. While a faster time would be preferable, a dramatic increase speed is not possible because of power dissipation and patient safety.

Safety: When operating within the human body, safety must be 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 the capsule must consider safety and biocompatibility.

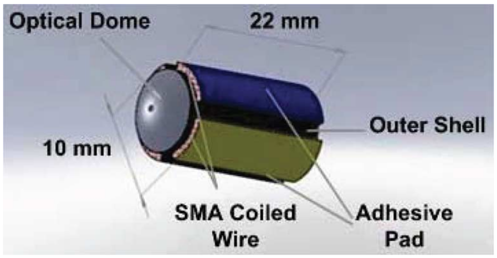

Fig. 1. Endoscope capsule robot.

Functionality: Some of the early concepts of such robots are now on the market. Families of sensing capsules provide temperature [19], [20], pressure [19], imaging [10], [11], [19], [21], pH data [19], drug delivery [21], tissue sampling [19], and polyp detection [8] to complement classic diagnostics, and one capsule delivers medication. There are also some further potential applications, such as the detection of obscure bleeding and the diagnosis of pancreatic cancer, esophageal cancer, and gastric cancer. It would be highly desirable to design a capsule robot that combines all the above functionalities and locomotion capabilities.

B. Conceptual Design

The authors' conceptual design of the capsule robot was inspired by the earthworm-like locomotive mechanisms proposed by Kim *et al.* [22]. In order to realize a two-dimensional locomotive mechanism, four spring-type SMA actuators are required to have long stroke and a strong-enough force to overcome resistance forces due to deformation of the small intestine. The actuator developed was integrated with clampers mimicking insect claws, and it has an earthworm-like locomotive mechanism. 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 an opposite rhythm. Based on the actuator design, the capsule robot has the ability to move forward and turn. It is worth noting that other important propulsion technologies have been applied to endoscopic capsules, such as the magnetic propulsion presented in [23]–[25].

The capsule robot measures 10 mm in diameter and 22 mm in length; see Fig. 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: the vision module, the sensor module, the communication module, the CPU module, and the battery.

Vision Module: A CCD image sensor is used in the capsule robot. This results in superior image quality but also in much greater power consumption due to the intense digital signal processing involved. The CCD image sensor is compassed by four LEDs of different wavelengths.

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

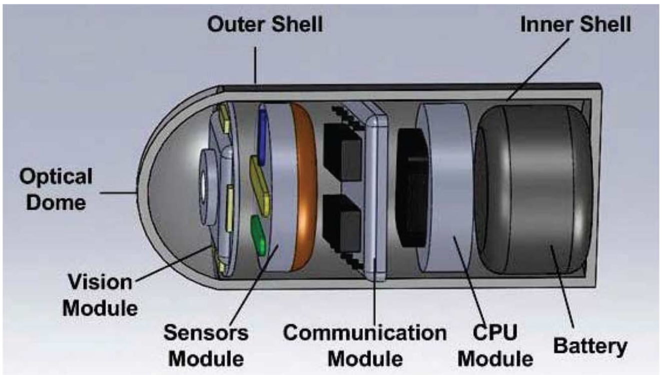

Fig. 2. Interior of the endoscope capsule robot.

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

CPU Module: The system's brain, the CPU, digitizes the signals that are provided by the sensors and vision modules. In addition, it performs additional processing of execution commands to control the SMA actuators.

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

In the 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 Fig. 2. Note that the design principles introduced in this section can be generalized to other clinical specialities besides endoscopy to expand optical and nonoptical sensing functionalities.

In Section IV, the navigation principles and control design of such a GI tract microrobot will be described.

IV. NAVIGATION AND CONTROL DESIGN OF CAPSULE ROBOT

This section presents the major issues in the navigation and control design of the capsule robot, intended to promote the expected learning outcome *E1*, the understanding of fundamental science and engineering principles in biorobotics.

A. Operating Modes

The operating modes of general robotics include teleoperation and semi- or full autonomy [26]. In the teleoperation mode, a human operator controls the robot and views the environment through the robot's vision system; this eliminates the need to incorporate artificial intelligence into the robot design. In contrast, in the semi-autonomous mode, the human operator controls the robot at some times, but not at others. While teleoperation is good at tasks that are unstructured and not repetitive, and/or when key portions of the task require object recognition or situational awareness, its disadvantages include the needs of the display technology, the limitation on communication links (bandwidth and time delay), and the availability of trained personnel. However, routine or "safe" portions of the task are handled autonomously by the robot in the semi- or fully autonomous modes. Recent advances in the field of robotics have developed fully autonomous robots for various applications [27].

For the design example of the pill-sized robot in the human's GI tract, the data rate can be dynamically adjusted by: 1) a change in the section of the GI tract (esophagus, stomach, small intestine, large intestine); 2) detection of tissue anomaly; 3) request of the physician. Taking these considerations into account, it was decided that the pill-sized robot should operate in two working modes: semi-autonomous and autonomous.

Semi-Autonomous Mode: In this mode, the robot can be activated and controlled by a clinician to anchor itself in a desired place to conduct a detailed sensing for temperature, imaging, pressure, pH data, or tissue biopsy. The robot's locomotion capability will allow the clinician to adjust the forward and turning motion of the capsule. These operations can also be realized remotely by the doctor via the internet.

Autonomous Mode: In this mode, the pill-sized robot autonomously navigates the GI tract generally in a forward motion with a constant speed. When some predefined events occur, the robot will follow predefined behaviors. The behavior-based robot programming is introduced in Section IV-B.

B. Behavior-Based Robot Programming

Robot architecture determines how the robot takes sensor information, processes it, and takes action accordingly. Robot architecture can be generally categorized as deliberative/hierarchical control, reactive behavior-based architecture, and hybrid systems that combine the two methods [28]. Deliberative systems are hierarchical in structure with a clearly identifiable subdivision of functionality, where communication and control occur in a predictable and predetermined manner, followed up and down the hierarchy. It relies heavily on representations of world models. It is well suited for structured and highly predictable environments, but the drawbacks include slow actions due to model building and deliberate planning, the requirements of world modeling, and the limited communication pathways.

For unstructured and uncertain environments, reactive behavior-based methods are more effective. A behavior is a mapping of sensory inputs to a pattern of motor actions that are then used to achieve a task. Reactive control tightly couples perception and actions, typically in the context of motor behaviors, to generate timely robotic responses in dynamic environments [28]. Due to its fast action and robustness, it has been commonly used in robotics research and practice since its inception in the 1980s. The key aspect in behavior-based control is how to coordinate behaviors. The popular subsumption architecture uses separated layers to represent individual goals that may happen concurrently and asynchronously. The behavior-based control was adopted in programming the microrobot in the GI tract, as explained here.

For the design example of pill-sized robot in the human's GI tract, the following behaviors are programmed for the robots:

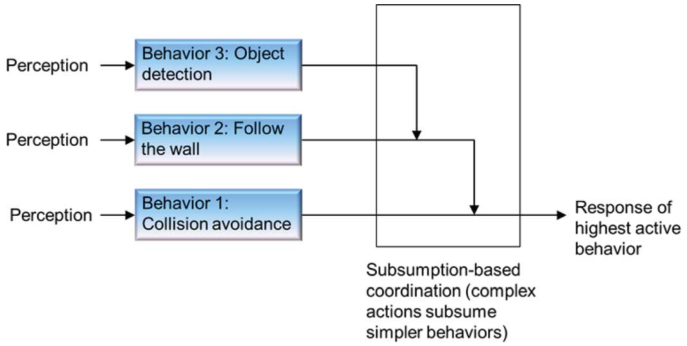

Fig. 3. Behavior-based robot programming for pill-sized robot navigation.

Behavior 1—Obstacle avoidance: The behavior to avoid potential collisions with obstacles in the environment. If the front sensor detects an obstacle in front of the robot, the robot avoids the detected obstacle by circumnavigating it.

Behavior 2—Following the wall: The behavior that the micro-robot navigates by following one side of the wall of the GI tract. The robot may operate under this behavior most of the time.

Behavior 3—Object detection: The behavior that the robot can slow down and take many pictures and sensing measurements when it detects malignant tissues. It can also issue an alert signal and send it to a human operator or a doctor to indicate the need for further checkup.

The above behaviors are organized in a subsumption-based coordination scheme (see Fig. 3), where the lower-level behavior has a higher priority for activation. That is, the robot may operate under "follow the wall" behavior when entering the GI tract; as soon as the sensor input indicates "obstacles" in its way, the "obstacle avoidance" behavior is activated; and the "object detection" behavior is at the higher-level, which is activated by the sensor input of "object." Note that the "obstacle" and "object" should be predefined for the robot, so that it can distinguish between them in real time through its sensor input.

V. LABORATORY MODULE TO SIMULATE CAPSULE ROBOT IN GI TRACT

A laboratory module was developed to simulate the navigation process of the capsule robot in the GI tract to support the learning outcome *E3*. The capsule robot is swallowed by the patient and travels through the esophagus, stomach, small intestine, and large intestine. During the robot navigation, the robot captures the information from the GI tract and transmits the data to the external console through the on-board communication module. Prior to the navigation, the external console can acquire a map of the GI tract and the approximate positions of the regions with potential problems. In the semi-autonomous mode, the clinician can navigate the capsule robot to the places for which he/she wishes to acquire more detailed information. To simulate the robot behaviors in the GI tract, a biomedical environment was built in the Webots simulator to imitate the GI tract.

In the following, the Webots simulator is first introduced, and the robot simulation development is then presented.

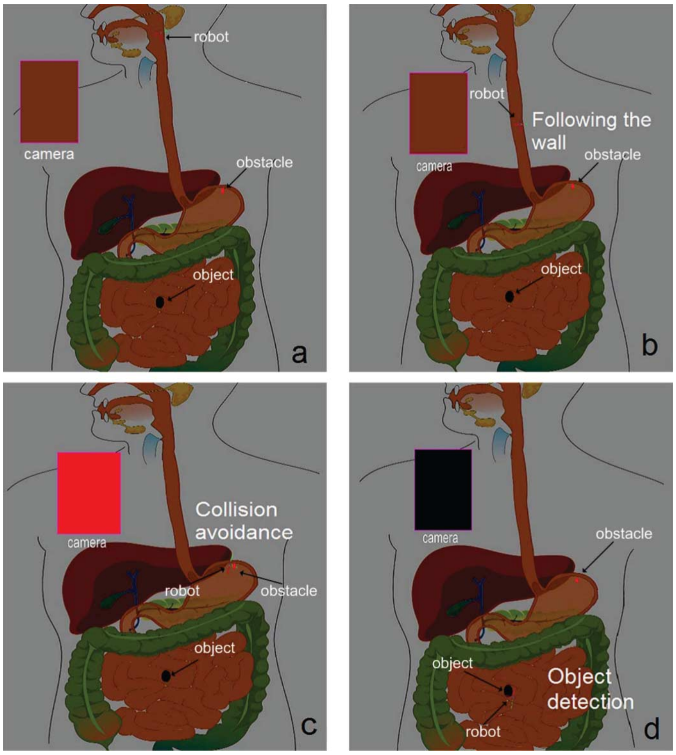

Fig. 4. Robot navigating in the GI tract. (a) Robot enters the GI tract. (b) Follow-the-wall behavior. (c) Collision-avoidance behavior. (d) Object-detection behavior.

A. Webots 3-D Robotic Simulator

Webots is a software for fast prototyping and simulation of mobile robots [29]. It offers a rapid prototyping environment, which allows the user to create 3-D virtual worlds with physical properties. The user can create mobile robots with various locomotion schemes, for example, wheeled robots, legged robots, or flying robots. Sensors and actuators can be added to the robots, including distance sensors, drive wheels, cameras, servos, touch sensors, emitters, and receivers. The user can program each robot individually to exhibit desired behaviors. Although developed primarily for robotics education and research, the Webots simulator can be used in other applications to model, program, and simulate physical devices in virtual worlds. Its Window-based interface makes it easy to learn for users who are familiar with the Windows operating system and C programming languages. It provides nonexperts (who have no extensive programming background) fast prototyping and visualization tools. As evidenced by student experiences shown in Section VI, it provides a unique opportunity for biomedical students to experience and learn software and simulations quickly.

Based on the conceptual design presented in Section III, a capsule robot was created in Webots, consisting of a body module, an actuator, proximity sensors, and a camera. The programming language C was used to program robot behaviors since all undergraduate students in Engineering learn C programming in their freshman year at Stevens.

B. Webots Simulation of Capsule Robot in GI Tract

The simulated pill-sized capsule robot was programmed according to the behavior-based navigation and control design described in Section IV. A scenario was simulated in which the

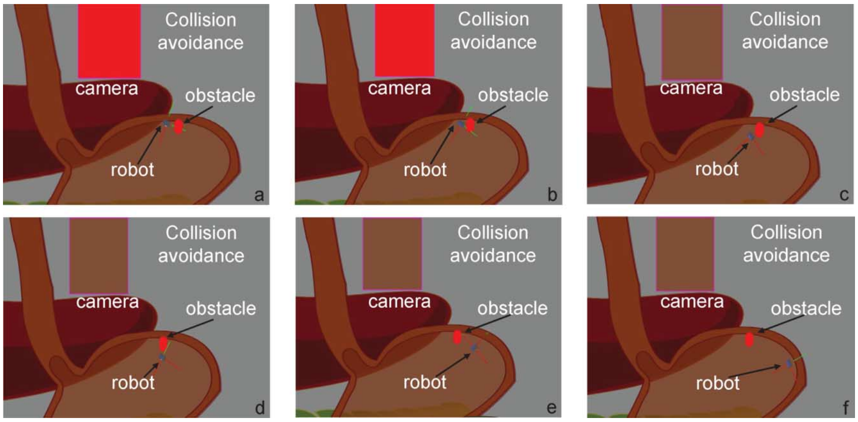

Fig. 5. Illustrations of the collision-avoidance behavior. (a) Front camera detects the obstacle. (b) Robot starts to go around the obstacle. (c)–(e) Robot avoids the obstacle. (f) Robot resumes the follow-the-wall behavior.

robot passes through the GI tract under the preprogrammed behaviors, as shown in Fig. 4, where the robot enters the GI tract in Fig. 4(a), and then navigates in Fig. 4(b)–(d) under the predefined following-the-wall, collision-avoidance, and object-detection behaviors, respectively. Note that the robot can be switched between the semi-autonomous and autonomous modes upon the request of the doctor by sending a wireless signal at any time. The rectangular block in each figure represents the real-time camera output during the navigation of the robot through the GI tract. The robot is equipped with proximity sensors (left and right) to detect position relative to the walls, and a front camera to detect objects.

To have a close view of the behavior, illustrations of the collision avoidance behavior are shown in Fig. 5, where the on-board camera in front of the robot detects an obstacle in Fig. 5(a), and the robot starts to go around it in Fig. 5(b)–(e). After it exits the collision avoidance behavior, the following-the-wall behavior is resumed to continue navigation. In the program, there are some control parameters that users can change, such as the robot's speed, its operating mode (semi-autonomous or autonomous mode), and delay time when objects of interest are detected.

VI. PILOT TESTING AND EVALUATION RESULTS

The materials described above were pilot tested as course modules in three courses during three consecutive semesters at Stevens Institute of Technology:

- EE/CpE 631 *Cooperating Autonomous Mobile Robots* (Spring 2011, Instructor: Yi Guo);
- BME 504/CpE 585 *Medical Instrumentation and Imaging* (Fall 2011, Instructor: Hong Man);
- BME 445 *Biosystems Simulation and Control Lab* (Spring 2012, Instructor: Arthur Ritter).

EE/CpE 631 is a graduate ECE course and can also be chosen by undergraduate students as a technical elective. The course discusses advanced topics in autonomous and intelligent mobile robots, and microrobots were introduced as a special topic during the second half of the semester.

BME 504/CpE 585 is primary a BME course and can be chosen by both undergraduate and graduate students. The course presents basic physics and practical technology associated with medical instrumentation and imaging. The materials developed were delivered as a case study toward the end of this course using one lecture session and one laboratory session.

TABLE I
NUMBER OF STUDENTS ENROLLED IN THE PILOT-TESTING COURSES

		BME		**ECE**	
Course	**Semester**	**Under-**	**Graduate**	**Under-**	**Graduate**
EE/CpE 631	Spring 2011	0	0	3	12
BME 504/CpE 585	Fall 2011	25	1	0	2
BME 445	Spring 2012	30	0	0	0
Total		55	1	3	14

BME 445 is an BME undergraduate course. It presents modeling and analysis of linear control systems. The associated lab session focuses on simulation and feedback control of physiological processes. The materials were presented as a case study in two lab sessions.

Table I summarizes the number of students who were directly impacted during the pilot testing.

The teaching of the materials includes the following components:

- a 5-min video clip on microrobots from the PBS series *Making Stuff Smaller*;
- discussions on the *grand challenge* to create semi-autonomous robots that can enter the human body to detect abnormality to destroy malignant tissue;
- lecture unit with the conceptual design of capsule robot and navigation principles;
- if time permits, students encounter various ideas on the topic by finding and presenting published papers;
- laboratory module to test the developed ideas and to run sample simulations provided on the Webots simulator platform.

At the beginning of the case study, the instructor shows an episode on the capsule endoscope technology in the PBS series *Making Stuff Smaller* [30], where the PillCam capsule technology is shown with a doctor and patient discussing its use. The video clip raises students' interest and fits well at the beginning of the case study. It is followed by presenting the "grand challenge" to create a semi-autonomous robot that can navigate in the human body to detect abnormality or to destroy malignant tissues, and allowing 5–10-min group discussion for idea development. Next, a lecture unit is provided to first review existing technology (as presented in Section II) and to introduce the conceptual design (as presented in Section III), and then to discuss the navigation and control principles and design (as presented in Section IV). Depending on the class time allocated for the case study, two different approaches were taken in the following class instruction.

1) In EE/CpE 631, there were two class sessions to allow each student to present published papers on the topic to complement the lecture unit, and grades were given to evaluate the quality of the presentation. Then, the students worked on a laboratory assignment themselves to simulate the pill-sized robots in the human GI tract using Webots, and final reports were collected and graded. This was made possible since the students had already learned how to use Webots simulation tools and practiced programming in earlier homework assignments during the course.
2) In the two BME courses (i.e., BME504 and BME445), the students generally had no robotic simulation experience, so the laboratory module was delivered in a laboratory session, where the Webots simulation software was first introduced, and the program to simulate pill-sized robot navigating in the GI tract was provided to students for them to run and observe. Homework assignments were assigned based on the given sample program so as to have students research further on the topic.

A. *Pedagogical Consideration*

The interaction of engineering analysis and design with biology holds great promise for synergies that both improve the understanding of biological processes and also provide novel engineering designs that are compatible with or mimic biological systems. Biomedical engineering is a multidisciplinary field combining elements of biology/physiology, electrical, mechanical, systems, and chemical engineering. How to educate undergraduate students in this multidisciplinary field so that they are equipped with the knowledge and skills required to meet the technological demand in the next few decades is a challenging issue. Contrary to the traditional knowledge-based or assessment-based education, challenge-based education provides an active learning environment and was recently adopted and implemented in a biotechnology course at Vanderbilt University, Nashville, TN, USA [31]. Its evaluation concluded that compared to traditional instruction, students in the challenge-based instruction achieve adaptive expertise much faster. Adaptive expertise requires a combination of two types of engineering skills: the ability to use subject knowledge appropriately and efficiently and the ability to think innovatively in new contexts [32], [33].

The challenge-based approach was adopted in the pilot testing of the case study to educate students from multidisciplinary backgrounds. The learning materials support challenge-based teaching. In a typical challenge-based implementation, a complex problem (the challenge) is presented to the students. Students then generate ideas based on what they already know and what they will need to know to solve the problem. This step can be materialized using the case studies described in this paper. In the second step, students discover different ideas on important aspects of the problem and key components of the knowledge taxonomy. This is supported by the lecture material. Next, students conduct research and revise their ideas, which is complemented by the design examples given. Students then "test their mettle," where laboratory modules are used to test students' designs. Finally, students present their solutions to the challenge in the form of homework/project reports and receive feedback. The sequential implementation cycle helps insure that the challenge-based principles are incorporated into learning materials to improve both knowledge and innovation. The research and revise, multiple perspectives, and "test your mettle" components primarily develop the knowledge component, while the generate ideas phase primarily develops innovative skills. The approach also develops skills in team building. Students share ideas and get multiple perspectives. These approaches increase motivation and awareness of the connections between their in-class experiences and their future work, lead to positive attitudes about learning for both students and teachers, and lead to significant increases in knowledge and innovation [33]. Overall, the case study and its pilot testing contribute to the practice of challenge-based teaching by providing a real example in cutting-edge biorobotics education that promotes adaptive expertise through rapid knowledge building and innovation.

B. *Evaluation Methods and Results*

An evaluation of the effectiveness of the materials was conducted based on students' homework/project reports and on an anonymous survey. The results are given in Sections VI-B.1 and VI-B.2.

1) Assessment of Student Work: Homework was assigned in both BME504 and BME445, and a final project was assigned in EE/CpE631. Table II lists the project and homework assignment questions. The homework assignment for BME504 and BME445 asks the students to run the demo program, observe the behaviors of the capsule robot, modify one of the behaviors by changing control parameters, and report on their experiences. The final project assigned in EE/CpE631 asks students to create their own capsule robot model, add proximity sensors (and/or any sensors applicable to the biological environment), propose new (or modify existing) path planning methods for the capsule robot to navigate in the GI tract, and simulate the path planning method that they propose. The differences between the homework and final project lie in the scope and the depth of the subject learned. Since EE631 is a robotics course and students have the whole semester to learn and apply robotic techniques, the final project gives them opportunities for innovative research experience on the subject. However, given the background of BME students, most of whom lack robotics background and

TABLE II
PROJECT AND HOMEWORK QUESTIONS

Project assignment	In the Webots environment, simulate the case study on a capsule robot in the human gastrointestinal (GI) tract; this includes creating your own capsule robot model, adding proximity sensors, proposing and implementing new (or modifying existing) path planning methods.
Hwk prob 1	Install Webots simulator, and report the installation procedure.
Hwk prob 2	Run the demo program, report your observations, and document behaviors of the capsule robot.
Hwk prob 3	Modify the provided codes, change control parameters such as object color and/or robot operating speed, report your experience.

TABLE III
STUDENT WORK ASSESSMENT RESULTS. N: THE NUMBER OF STUDENT WORK ASSESSED. LOW: 25TH PERCENTILE. MIDDLE: MEDIAN. HIGH: 75TH PERCENTILE. THE GRADE IS IN THE SCALE OF 4

	Assessment Instrument (Student work assessed)			**Student Performance Grade (N)Low:Middle:High**		
Outcome	**EE/CpE631**	**BME504**	**BME445**	**EE/CpE631**	**BME504**	**BME445**
E1	project	hwk prob 2	hwk prob 2	(15) 3.12:3.4:3.6	(20) 3:4:4	(13) 4:4:4
E2	project	hwk prob 2	hwk prob 2	(15) 3.12:3.4:3.6	(20) 3:4:4	(13) 4:4:4
E3	project	hwk prob 1	hwk prob 1	(15) 3.12:3.4:3.6	(20) 2.5:4:4	(13) 3.5:4:4
E4	project	hwk prob 3	hwk prob 3	(15) 3.12:3.4:3.6	(20) 2.5:4:4	(13) 4:4:4

TABLE IV
ANONYMOUS SURVEY QUESTIONS

No.	Survey Questions
1	The lecture motivated me towards the subject of micro/nano-robotics in biomedical applications.
2	My understanding of micro/nano-robotics BEFORE I took the case study:
3	My understanding of micro/nano-robotics AFTER I took the case study:
4	The lecture materials helped me to understand micro/nano-robotics.
5	The case study helped me to learn science and engineering principles in robotics.
6	The case study helped to enhance my interdisciplinary skills.
7	The case study helped to enhance my capability on critical thinking.
8	Overall, the case study improved my learning experience.
9	I had the knowledge and skill to complete this lab exercise without additional study beyond the lecture.
10	The lab exercise was easy to carry out and did not take me too much time.
11	The lab assignment was reasonable and did not take me too much time.

software experience, and also the limited class time given to the biorobotics topic, the homework assignment is within the scope of their experience and learning but does not involve research.

The results of homework/project evaluation and its impact on the expected learning outcomes (listed in Section I-C) are summarized in Table III, where student grades are listed in the Low (25%), Middle (50%), and High (75%) levels. It can be seen from Table III that the expected outcomes outlined in Section VI-A were effectively assessed, and encouraging results are obtained. Note that the number of the student homework assessed is small in BME445 because group reports were allowed in this course to facilitate group collaboration. It is also worth noting that the assessment results for BME445 are better than BME504 since the authors improved the lab menu instruction for BME445 based on the pilot-testing experience of BME504.

2) Survey Results: Anonymous surveys were conducted in all three courses to evaluate the effectiveness of the materials. Table IV summarizes the main survey questions posed, where questions 1–8 were asked in all three courses, and questions 9–11 were asked only for BME courses on the lab experience.

Questions 2 and 3 have a numerical value from 1 to 5 to choose from, where 5 represents the highest level of understanding. All other questions had five choices: *Strongly Agree, Agree, Somewhat Agree, Disagree, and Strongly Disagree*. Representing the choices from *Strongly Agree* to *Strongly Disagree* using the numbers from 5 to 1, the survey results are summa-

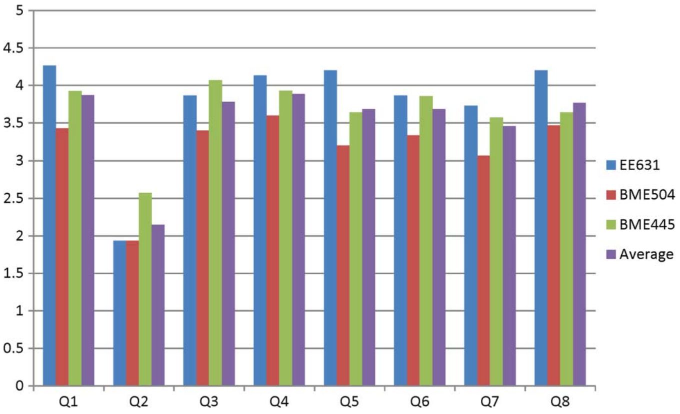

Fig. 6. Results on questions 1–8 listed in Table IV. "Average" shows the average of the three courses.

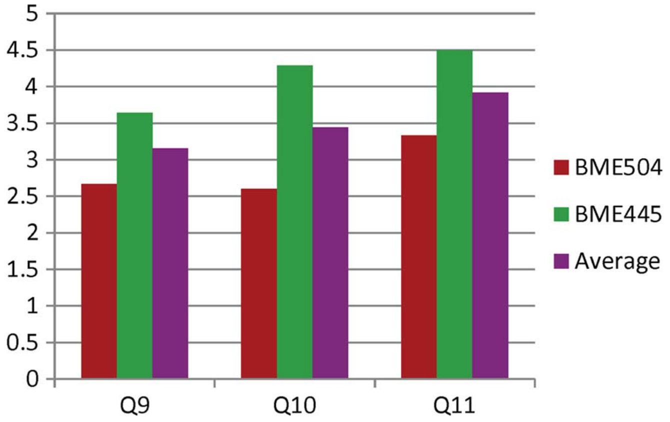

Fig. 7. Results on questions 9–11 listed in Table IV about the lab session. 5: Strongly agree. 4: Agree. 3: Somewhat agree. 2: Disagree. 1: Strongly disagree.

rized in the following figures. Fig. 6 shows the average scores of each of the eight main questions for each of the three courses. Fig. 7 shows the average scores of each of the additional three questions about the lab session for the two BME courses.

From the survey results shown, it can be seen that the materials helped students' motivation (average 3.87), understanding (average 3.78), science and engineering principles (average 3.68), interdisciplinary skills (average 3.69), and critical thinking (average 3.46). The overall learning experience is also good with an average 3.78. Particularly, student understanding *before* and *after* the case study was improved from an average 2.15 to 3.78. The lab exercises and assignments were both easy to use (average 3.44) and did not take too much time (average 3.92).

It is also noticed that differences exist in the outcomes between the three courses. The ECE course received a better rating for most of the survey questions compared to the BME courses. This is because ECE students are better motivated on the topic of robotics. They had already been taught general topics in robotics in the first part of this course, so it was easier for them to grasp the ideas, and they could program independently using the provided simulation platform. In contrast, although most of the BME students can program in C, most of their programming experience is in MATLAB. The robotic simulation platform, Webots, is new to BME students. It was observed that some students had difficulties in the first pilot test during the lab session of BME504. Accordingly, the authors modified the materials and included more detailed instructions in the lab menu for BME students. The survey results show the effectiveness of this modification, as evidenced by the fact that the rating of BME445 improved for each of the survey questions compared to BME504.

The students were also asked to provide written comments about the learning experience and how it can be improved. The responses include the following.

- "The video shown during the lecture was helpful and I liked the group discussion of answering the questions."
- "I thought the directions were extremely clear and easy to follow. It took around three minutes to complete the lab."
- "I think the case study went really well. I mostly enjoyed the lecture on nanorobotics."
- "The case study was enjoyable because it's related to a real life scenario. Watching the pill-camera move towards the blockage was the most appealing part."

C. Lessons Learned

The authors also learned a few lessons. The first lesson learned is the different background of ECE and BME students in robotics, the simulator, and programming skills. The second lesson learned is that the most difficult part of the lab for students is the installation of the software Webots. Webots is a commercial robot simulator, for which a 30-day trial version with limited functionalities is freely downloadable from the Web. The trial version needs registration 24 h prior to installation, and a few students failed to do this before the lab session. Also, the software has many different versions, and the Web links for some of the early versions were hidden and not easy to find. The sample program was developed using an early version of Webots, and compatibility with later versions of the simulators is a problem. Recognizing these difficulties, during the instruction of the second BME course (BME445), the authors improved the lab instruction to give greater detail and more direction and have the graduate student who developed the sample program assisting the lab session. Eventually, every student in BME445 was able to run the lab successfully. A third lesson learned is that conducting the lab exercises in groups is helpful for BME students, as the students with better software background can help those who are less strong in that aspect.

VII. CONCLUSION

Motivated by the need of developing new teaching materials for BME students, a case study of a pill-sized capsule robot operating in the human GI tract was carried out and has been presented here. The case study is composed of a conceptual design of the microrobot and a laboratory module to simulate the navigation of the robot in the human's GI tract. Modern robotic technologies, including robot building components, operating modes, and behavior-based programming, are taught through the case study. The students also experience robotic simulation software and practise programming. The case study was pilot tested as a course module in three ECE and BME classes at Stevens. The evaluation results show enhancement of students' understanding of microrobotics, interdisciplinary skills, and critical thinking. The authors are currently building an online site for the case study to assist further dissemination.

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