AC 2010-503: MEETING THE EDUCATIONAL CHALLENGE IN MICRO/NANOROBOTICS FOR BIOMEDICAL APPLICATIONS

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Meeting the Educational Challenge in Micro/nanorobotics for Biomedical Applications

Abstract

We present the progress of our NSF CCLI project to design teaching materials on micro/nanorobotics for biomedical engineering students. We have developed a case study and a laboratory module, both of which are centered on a vitamin pill sized microrobot navigating in the human's GI tract. In particular, we built a simulation module in Webots 3D simulator, where the microrobot navigates along the GI tract and detects abnormality through an onboard camera. Using the case study and the laboratory module, we teach students building components of a microrobot, and basic behaviors for robot navigation and detection.

Introduction

In the same way MicroElectroMechanical Systems (MEMS) technologies provided new medical devices in the 80s, recent development in nanotechnology is enabling the manufacturing of nanobiosensors and actuators to improve cell biology interfaces and biomolecular applications. As a consequence, nanorobotics and nanomedicine have evolved from pure science fiction to a rapid growing research area which may lead to a real implementation in a few decades. According to a 1997 report by a panel of experts sponsored by the U.S. Department of Defense, nanomedicine could become a reality by the year of 2020, and "possible applications include programmable immune machines that travel through the bloodstream, supplementing the natural immune system; cell herding machines to stimulate rapid healing and tissue reconstruction; and cell repair machines to perform genetic surgery"[1]. Also, the U.S. National Institute of Health (NIH) Roadmap's new Nanomedicine Initiatives released in 2003 envisioned that "the cutting-edge area of research will begin yielding medical benefits as early as 10 years from now".

In future decades, the principle focus in medicine will shift from medical science to medical engineering, and the design of microscopic and molecular machines will be the consequent result of techniques provided from the biomedical knowledge gained in the last century[2]. Market demand for professionals with advanced degree training relevant to micro/nanorobotics and nanomedicine will be fueled by the permeation of new discoveries in the field. In this CCLI proposal, we address how to educate our engineering undergraduate students in the subject of micro/nanorobotics aiming at biomedical applications so that they are well-prepared with the knowledge and training to fulfill the technology demand when entering the job market.

Over the last decade, there has been a significant growth in the number of undergraduate Bio-medical Engineering (BME) programs, and the number of students enrolled in these BME programs. Currently there are 117 BME academic programs in the U. S. that are profiled in the Whitaker Foundation curriculum database[3]. According to the statistics collected by the Whitaker Foundation, the number of undergraduate enrollment has increased from around 5,000 in 1993 to over 12,000 in 2003[4]. Based on a forecast by the US Bureau of Labor Statistics, biomedical engineering jobs will climb almost twice as fast as the overall average for a 26.1 percent gain by

2012 while overall job growth is projected to be 14.8 percent. The national growth of the BME programs calls for new educational materials supporting biomedical engineering.

Micro/nano-robotics for biomedical applications is an emerging area that has received advancement during the last decade. Despite of books/textbooks in nanotechnology, for example, there are a growing number of articles appearing in journals and conference proceedings in biomedical micro/nano-robotics[5-7]. 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/nanorobotics are limited to a few graduate courses offered at limited colleges. There is a general lack of learning materials on microrobotics in undergraduate education. In this NSF CCLI project, we aim to fill the missing gap, and to teach undergraduate microrobotics and also principles of nanorobotics by drawing inspiration from the microrobotics field.

Existing technology has enabled the design and building of a micro-scale device that can be introduced into the body to perform various medical activities[8]. For example, the PillCam developed and marketed by Given Imaging can enter a patient's gastrointestinal (GI) tract and transmits images of different parts of the body such as the small intestine and the esophagus. In this paper, we present our progress in designing learning materials based on a microrobot that can be created with existing technology, and can enter human's GI tract. We describe the development of a laboratory module to simulate such a device navigating in the biomedical environment, with the goal to train student robot programming and basic robotic navigation principles.

A Vitamin-Pill Sized Vehicle in GI Tract: A Case Study

The lab module will be centered on the grand challenge: create a semi-autonomous robot that can navigate in human body to detect abnormality or to destroy inimical tissues. It will be built upon multiple perspectives of the grand challenge. To materialize the challenge, a case study will be designed based on the existing technology of the PillCam capsule (Given Imaging, Ltd., Yoqneam, Israel). This is a commercial device of 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 limitations limit its application to the GI tract. For more general application in the blood stream, the maximum dimension of the capsule should be smaller than 1µm (1000 nm), since the smallest capillaries are around 3 µm in diameter. Red blood cells, with their biconcave shape and flexible membrane properties can bend to fit through the smallest capillaries. The case study starts with the idea of creating a device such as the PillCam capsule, reducing the size, and adding functionality and mobility.

To design such a device, we need to consider biological compatibility of the shell, sustainable power supply, imaging, data transmission, navigation and tracking capability. As in the design of a space capsule, we are dealing with a volume limited system. In addition, to conserve power, the density of the capsule should be adjusted so as to approximate that of plasma (about 1.03 gm/cm^3). As a first approximation, 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. The overall system design will integrate these functions. We envision a modular approach so that as new technologies are developed they can be readily integrated into the vehicle to evaluate their performance and capabilities. The goal of the design example is to illustrate necessary micro/nanorobot components and demonstrate associated technologies to achieve the required functionalities.

Micro/Nanorobot Components and Techniques

To facilitate teaching the lab module, we first briefly describe the nanorobot components including sensors, actuators, propulsion systems, and their associated techniques. The goal is to teach students existing engineering techniques in a systematic way towards solutions to micro/nano-robots in biomedical applications, which can be improved when new techniques become available. In the following, we describe briefly the important nanorobot components that support the case study described above.

Shell: The outer shell of the device should be biocompatible material. An inner shell, containing three compartments, is separated from the outer shell by 5 nm to 10 nm. The space in between will serve as a ballast reservoir to adjust the overall density to aid buoyancy. Carbon dioxide gas, produced by the power supply will be trapped between the two shells. The overall dimensions will be approximately 4 μm by 2 μm. The shell design can draw inspiration from underwater robots, where hydrostability is considered. For use in the GI tract, with gravity providing the major force, weighting the front end of the vehicle overcomes this problem. In the blood stream, with possible turbulence encountered in larger vessels and through heart valves, the hull has to be designed more like that of a submersible, with a keel and some stabilizer appendages.

Actuators: Piezoelectric materials have been used as actuators or sensors in bulk or thin film forms. Micron-sized piezoelectric fibers are available and have been used in commercial products[9]. Used in the GI tract, nanoscale piezoelectric materials can generate voltages under the peristaltic action of the GI tract and convert mechanical energy into electrical energy. This could be one solution to the power and propulsion subsystem.

Another type of nano-actuators comes from the biological systems: protein motors. The classical actin-myosin power stroke that converts chemical energy of ATP to mechanical work of muscle is probably the oldest known. More recently, the microtubule motor protein families kinesins and dyneins have been identified[10, 11]. The kinesins constitute a superfamily of protein motors similar in structure to myosin that are involved in motion of the cytoskeleton of cells. The dyneins are also linear microtubule track motors which are not related to the kinesin superfamily. They are the largest of the known molecular motors and are also among the fastest. They are highly specialized for sliding the microtubules that are responsible for the beating of cilia and flagella. For biomedical applications, the most interesting of these molecular motors is the ATP synthase enzyme.

Sensors: In a biomedical application, the sensing of local pressure, temperature through infrared capability, proximity to surfaces through ultrasound, pH changes, and specific protein structures

through functionalized surface probes would provide useful feedback data. Some of these sensors are presently being developed at the nanoscale[12, 13]. Due to the relative maturity of medical imaging techniques, we focus on biomedical imaging techniques for sensory purpose.

Medical Image Processing: The imaging module in the nanorobot usually includes three functions: 1) capturing images and video sequences as the robot navigates and transmitting them to an external data recording device, 2) detecting abnormal appearance, 3) detecting important landmarks that can help the positioning and navigation subsystem. Critical constraints for the imaging module may include low computing power, low on-board memory, low energy supply, low wireless transmission bandwidth, and above all high data volume. Due to the large data volume, image and video coding is essential for effective transmission within bandwidth limited media. Within each image block, coding normally takes three steps, i.e., transform, quantization and entropy coding[14, 15]. Wireless data transmission requires significant power consumption, and it should be kept at minimum level as possible. For biomedical applications, adaptive data transmission schemes will be adopted that can provide most critical information and minimize redundant information. For the GI tract example, the data rate can be dynamically adjusted by following events: 1) change of sections in the gastrointestinal tract (esophagus, stomach, small intestine, large intestine), 2) detection of tissue anomaly, 3) upon request by the physician.

Webots 3D Simulation of a Microrobot in GI Tract: A Laboratory Module

Webots is a powerful robot simulator that provides 3D simulation environment for modeling, programming, and simulating mobile robots. It supports E-pucks mini-robots and many other popular robot models. It has been used by over 450 universities and research centers worldwide. It was recently used as the platform for a robot programming contest, “Rat's Life”, to promote research results and stimulate further interest in bio-inspired robotics control.

We built a microrobot model on the platform of Webots simulator, as shown in Fig. 1.

Sensors: The microrobot includes three proximity sensors and one camera. The sensors are located in front, and on the left and right sides of the microrobot, respectively, to provide proximity information to surfaces through ultrasound. The camera is placed at the front of the robot and used for capturing images and video sequences as the microrobot navigates and transmits them to an external data recording device (which might be a computer).

Actuator: The microrobot is propelled by two motors, each of which generates velocity v_{right} and v_{left}, respectively. If $v_{right} = v_{left}$, the microrobot moves straight (forward for positive velocities and backward for negative velocities). Otherwise, the microrobot turns right ($v_{right} < v_{left}$) or left ($v_{right} > v_{left}$).

We built a biomedical environment in Webots simulator to imitate part of GI track, as shown in Fig. 2. In this environment, we assume there exist three inimical tissues (A, B and C) on the inner surface of the GI tract.

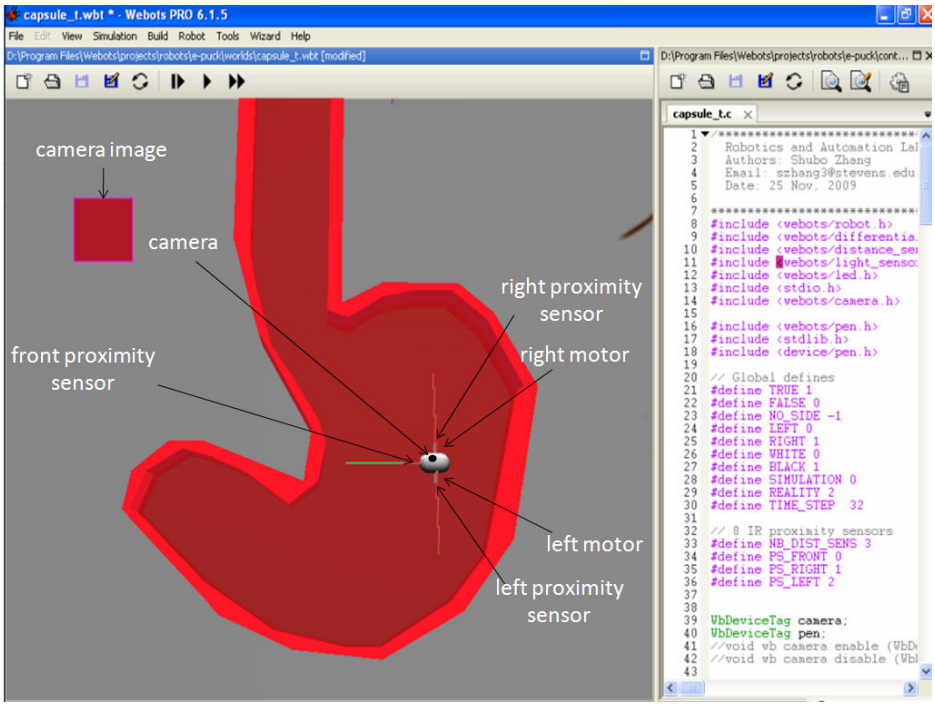

Fig. 1: A microrobot model built in the Webots 3D simulator. Left: the graphic user interface (GUI) showing a microrobot in GI tract (The image captured by the onboard camera is displayed at the top left corner of the GUI). Right: the C/C++ programming environment.

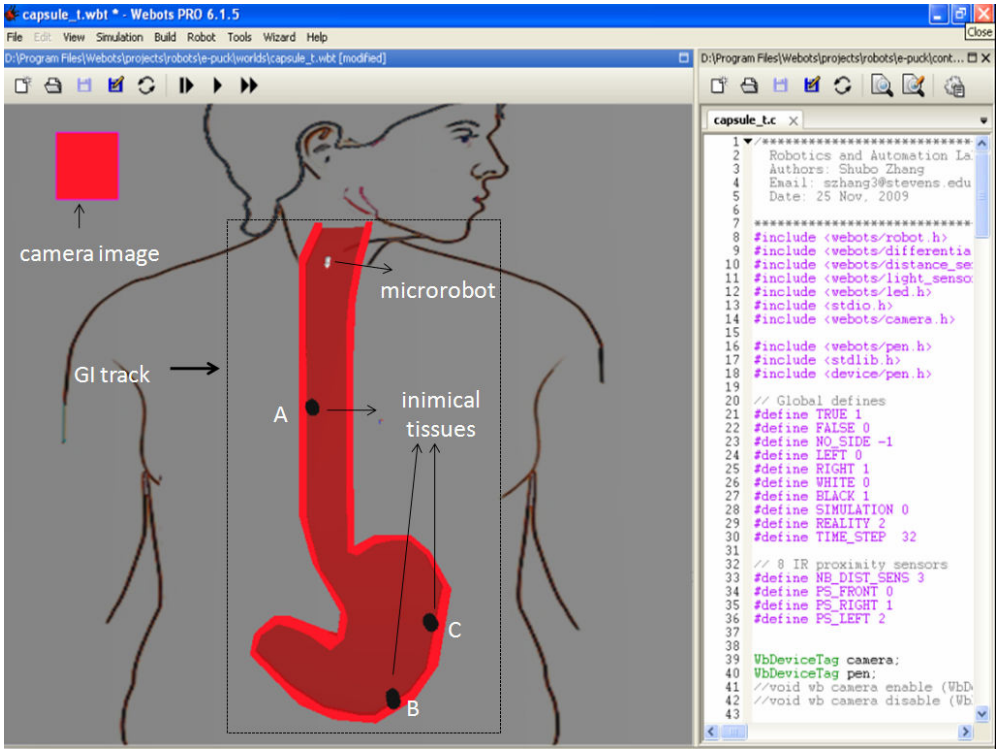

Fig. 2: The map of the GI tract built in the Webots simulator. The image captured by the onboard camera is displayed at the top left corner of the GUI.

We simulate a scenario that the microrobot navigates through the GI tract, detects inimical tissues through capturing images or video sequences, and then transmits the images and videos to the computer for display. The microrobot implements this biomedical application with two behaviors, *following the wall* and *obstacle avoidance*.

Following the wall: it is the behavior that the microrobot follows one side of the GI track wall to navigate. In order to implement this behavior, we set $v_{right} = v_{left}$ if and only if $d_r = s$ and $d_r < d_l$, where d_r and d_l are the distances returned by the right and left proximity sensors, respectively, and s is a safety threshold.

Obstacle avoidance: it is the behavior to avoid potential collisions with obstacles in the environment (here, the inimical tissues are denoted as "obstacles"). If the front sensor detects obstacles in front of the robot, the robot avoids the detected obstacle by turning away from it. For instance, in Fig. 3 (a), the microrobot starts to navigate by following the right side of the wall in the GI tract. After a while, the microrobot detects the abnormality and the operator confirms the inimical tissue A through the video sequences which are captured by the camera, as shown in Fig. 3 (b). The microrobot then compare d_r and d_l to determine whether to turn left (if $d_r < d_l$) or right (if $d_r > d_l$). In our biomedical environment, the microrobot avoids inimical tissue A by turning left and continues navigation by resuming the behavior of *following the wall* until it meets the other inimical tissues B and C, as shown in Fig. 3 (c), (d). The complete navigation trajectory of the microrobot is shown in Fig. 4.

By implementing the navigation scenario of a microrobot in the GI tract, we can teach students the main components of a robot (sensors and actuators), and two main behaviors for navigation (following the wall and obstacle avoidance). The laboratory module is developed by C/C++ programming, and the source codes are available to students for modification of navigation parameters.

Conclusions

During the past decade, there has been a significant growth in the number of undergraduate Bio-medical Engineering (BME) programs and the number of students enrolled in these programs. Motivated by the lack of teaching materials on microrobotics for BME students at US colleges, we aim to develop materials to teach undergraduate microrobotics and also principles of robotics navigation. In this paper, we present our results in designing a case study and a laboratory module centered on a vitamin pill sized microrobot navigating in the human's GI tract. In particular, we built a simulation module in Webots 3D simulator, where the microrobot navigates along the GI tract and detects abnormality through an onboard camera. Using the case study and the laboratory module, we teach students the building components of a microrobot, and basic behaviors for robot navigation and detection. Future work includes pilot testing and formal evaluation of the developed materials.

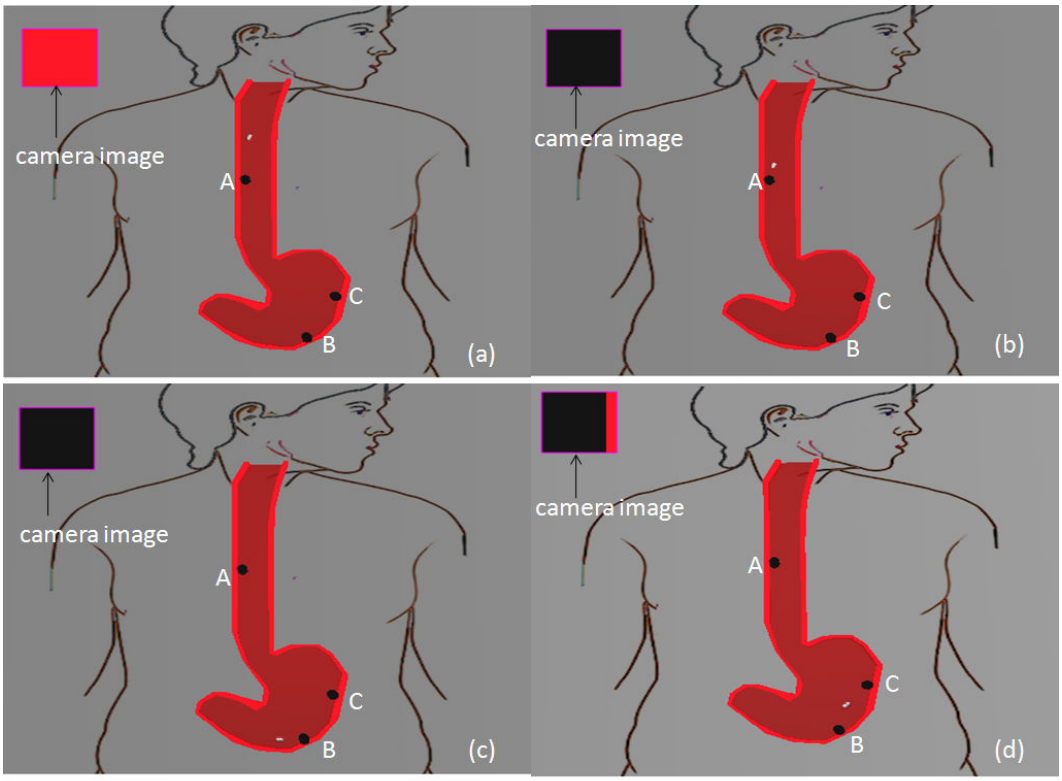

Fig. 3: The microrobot navigates in the GI tract to detect abnormality. (a): Navigation starts; (b), (c), and (d): The moments that the microrobot detects the inimical tissues A, B and C, respectively. The images captured by the onboard camera are displayed at the top left corner of the GUI.

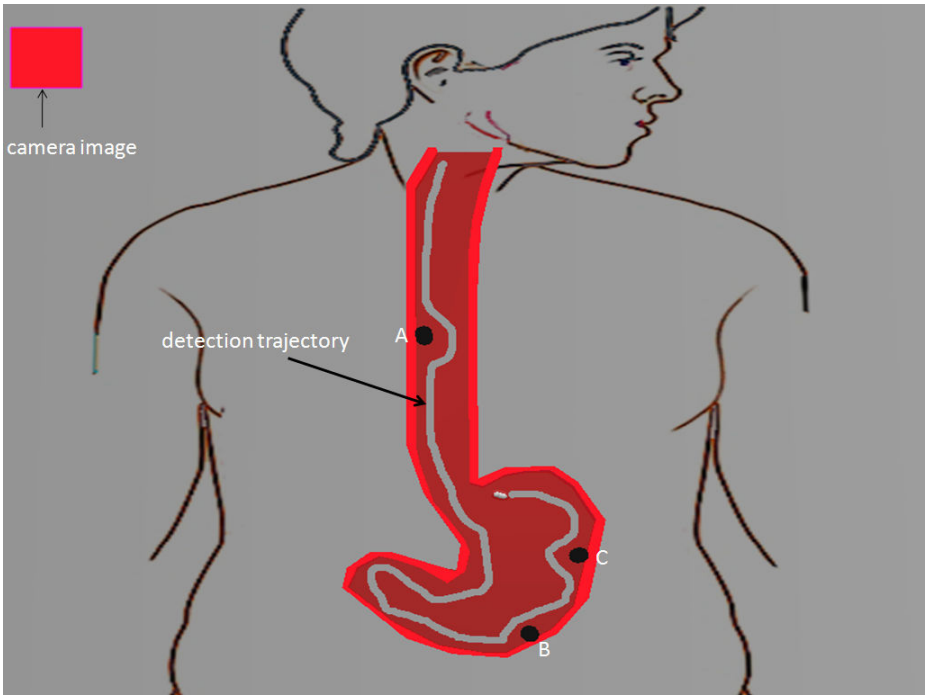

Fig. 4 The complete navigation trajectory recorded by the simulator.

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