Chapter 6
Capsule Robot in Gastro-Intestinal Tract: A Case Study for Robot Programming and Navigation

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Abstract We present a case study of a pill-sized capsule robot operating in the human's gastro-intestinal (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 are provided including sensors, actuators, processing, communicating, and power supply. The laboratory module is built on the 3D Webots simulation platform. Behavior-based robot navigation methods are introduced to program the robot to navigate in the human's body.

6.1 Introduction

It is estimated that 19 million people in the United States may suffer from diseases related to the small intestine, including obscure bleeding, irritable bowel syndrome, Crohn's disease, chronic diarrhea, and cancer. However, these pathologies are difficult to diagnose through traditional methods, such as push enteroscopy, wired endoscopes, and radiology [1]. Another disadvantage of traditional methods is that using an endoscope to inspect the inside of the human body is a rather uncomfortable procedure for a patient. Apart from that by using a conventional

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endoscope there are potential side effects, such as perforation of organs, infection, and hemorrhage [2]. There are also various inspections of the digestive system such as the colon and stomach, and it is very difficult for the conventional endoscope to reach duodenum and small intestine.

6.1.1 Existing Capsule Endoscopy Technologies

Wireless capsule endoscopy has been commercially available since 2001. For a patient, such capsules offer a convenient examination with minimal preparation and immediate recovery [3]. The main vendors are Olympus Optical [4], Given Imaging [5], and the RF System Lab [6]. Given Imaging has developed two distinct capsules: PillCam ESO [7] for the esophagus and PillCam SB [8] for the small bowel. Both capsules measure 11 mm in diameter and 26 mm in length. RF data transmission at 433.10 MHz to an external antenna network enables the transfer of 2–8 frames per second. The device, powered by silver oxide batteries, can provide over 5 h of continuous video recording.

The RF System Lab has been developing the Norika3 system since 1998. Unlike PillCam, which uses complementary metal-oxide semiconductor (CMOS) image sensors, this device uses a charge-coupled device (CCD) image sensor. This results in superior image quality but with much greater power consumption due to the intense digital signal processing involved. To tackle the power requirement, the capsule transmits raw sensor data, while the processing, which consumes over 90 % of the power, occurs outside the body. The capsule, 9 mm in diameter and 23 mm long, is the smallest endoscopy capsule. It has four illumination LEDs with different light wavelengths. Three-dimensional coils within the capsule allow optimum power recovery from the inductive link. 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. The second-generation capsule Sayaka [6], introduced in December 2005, operates on the same principle but has the lens on its lateral surface instead of its end. The imaging device is rotated within the capsule by steps of 7.5 degrees and provides approximately 30 frames per second, giving overall higher resolution.

The SmartPill Corporation has integrated temperature, pressure, and pH sensors into a single capsule, the Smart-Pill pH.p [9]. The company promotes the device as a complement to endoscopy with the potential to replace gastric emptying scintigraphy. The SmartPill GI Monitoring System includes the capsule, a wireless data receiver, a receiver docking station, and MotiliGI software. A powerful magnet activates an internal latching switch that provides a connection between the electronics and the battery. Once the capsule is activated, it begins working and transmits data to the mobile-phone-sized receiver (worn on the patient's belt). The receiver, in turn, transfers the data wirelessly to a PC in real time. The SmartPill, which has a 13-mm diameter and is 26 mm long, measures temperature to an accuracy of ±0.5 °C, pressure resolution to ±3.6 mm HG, and pH to ±0.28.

It uses the sensor data in addition to real and elapsed time measurements to provide gastric emptying time, combined small and large intestine transit time, contraction patterns, and a motility index. To optimize the device's performance, the pill samples at a high rate for the first 24 h and then at a decreased rate as the pill approaches the end of its journey. MotiliGI can plot the acquired data against time, providing invaluable information in the diagnosis of motility disorders such as gastroparesis (slowed passing of solids from the stomach). The pill underwent extensive clinical trials and consequently received FDA approval in July 2006.

Another interesting area of swallowable capsule technology is in vivo drug delivery or, conversely, sample extraction. Pharmaceutical Profiles is researching drug absorption using the patented Enterion capsule [10] developed by Phaeton Research. The capsule is 32 mm long and 11 mm in diameter. It can hold up to 1 ml of liquid or powder, which can expel at a target site in the body. The capsule contains a small amount of gamma-emitting tracer, allowing precise tracking in real time using an external gamma camera. When the capsule reaches the target area, an external electromagnetic field actuates the capsule's piston, ejecting the payload. The shell then passes harmlessly out of the body. Another piston-based capsule, proposed by the State University of New York, extracts substances from a target location in the gastro-intestinal (GI) tract in a similar fashion [11].

6.1.2 Robotic Capsule Technology

The commercial wireless capsule endoscopy we aforementioned has an advantage in reducing pain and discomfort of the patient due to its wireless nature. However, they must move passively from the mouth to anus by the peristaltic waves and gravity. If a capsule could be activated and controlled by a clinician to temporarily resist peristalsis and anchor itself in place in the gastrointestinal tract, additional tools for tissue biopsy, drug delivery, and cleaning or cauterizing angiectasias could be integrated into the device design to enhance its functionality. Due to the intestine's unstructured nature of the environment, which has loose, elastic, slippery walls [12], developing robotic capsules able to move inside the GI tract is more challenging. Nevertheless, recent research has been conducted on developing locomotion mechanisms into microcapsule robots. There are some capsule robots with anchoring mechanism that can resist the body's peristaltic forces to anchor itself to the intestinal lining at a desired location. Kim et al. [13] built and tested a capsule powered by eight individual shape memory alloy (SMA) actuators and embedded with microhooks to provide traction. Later, the same group developed a micromotor-actuated locomotion system for capsules inspired by canoe-paddling [14]. Quirini et al. [15] have proposed a pill-sized 12-legged endoscopic capsule for locomotion in the lower gastro-intestinal tract. Other locomotion methods that have been attempted for propulsion inside body cavities include a fin type electromagnetic actuator [16], a multi-joint endocavitary robot actuated by piezoelectric elements [17].

In this chapter, we present 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 platform of the Webots simulator. The objective of the laboratory modules is to show 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. In order to achieve autonomous navigation, behavior-based robotic navigation technique is first reviewed, and a few behaviors are created to program the robot navigation functionalities.

The rest of the chapter is organized as follows. In Sect. 6.2, we present a conceptual design of the pill-sized robot, and introduce its building blocks. In Sect. 6.3, we discuss the method to control the micro-robot navigating in the human's GI tract. Then in Sect. 6.4, a laboratory module is built to simulate different robot behaviors based on the Webots robot simulate platform. Finally, the chapter is concluded with brief remarks in Sect. 6.5.

6.2 Conceptual Design of Capsule Robot

6.2.1 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 [6], is the smallest endoscopy capsule.

Speed: A standard colonoscopy is completed in approximately 20 min–1 h, 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 [9, 18], pressure [9], imaging [6, 7, 9, 10], pH data [9], drug delivery [10], tissue sampling [9], and polyps detection [4] 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.

6.2.2 Application Scenarios

The proposed capsule is a self-contained micro-system that can perform sensing and actuating functions 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-D, 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 endoscopy process which can take around 5–20 h [19], 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 to get a map and the approximate positions of all GI tract regions with potential problems. In the 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 also be realized remotely by the doctor through the Internet.

6.2.3 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 in [20]. 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

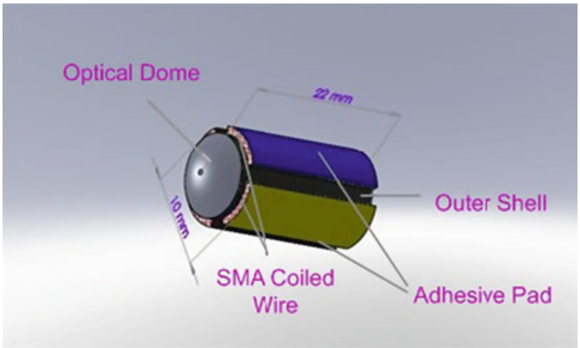

Fig. 6.1 The endoscope capsule robot

as to its biocompatibility. Combined with its small strain capability, this was determined to be a 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 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. [21]. In order to realize a 2-D 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 has the ability to move in 2-D, moving forward and turning, which enables it to implement tracking and navigation in the GI tract.

The capsule robot measures 10 mm in diameter and 22 mm in length, see Fig. 6.1. 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 image sensors, this device uses a CCD image sensor. This results in superior image quality but with much

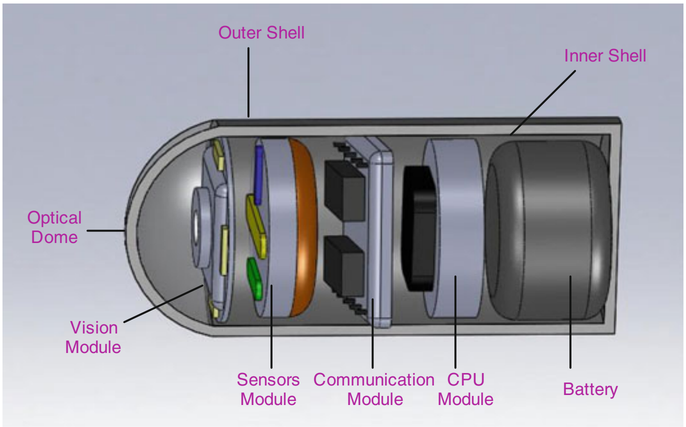

Fig. 6.2 Inside of the endoscope capsule robot

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.

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

Communication Module: The communication module can then both transmit and receive the signal to communicate with the outside of 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 sensor and vision modules. On the other hand, the CPU performs additional processing of execution commands, which operates the SMA actuators in a controlled manner.

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 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.

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 Fig. 6.2.

6.3 Navigation and Control Design of Capsule Robot

6.3.1 Operating Modes

The operating modes of general robotics include teleoperation, semi- or fully autonomy [22]. In the teleoperation mode, a human operator controls the robot, who only views the environment through the robot's eyes, and the robot design does not have to figure out artificial intelligent. Instead, in the semi-autonomous mode, the human operator might control the robot sometimes and human does not have to do everything. While teleoperation is good at tasks that are unstructured and not repetitive, and/or key portions of the task require object recognition or situational awareness, the disadvantages of the method include needs of the display technology, the limitation on communication links (bandwidth and time delay), and the availability of trained personnel. On the contrast, 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 in various applications [23].

For our design example of pill-sized robot in the human's GI tract, the data rate can be dynamically adjusted by the following events: (1) change of sections in the 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 pill-sized robot operates in two working modes: semi-autonomous mode and autonomous mode.

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

Autonomous Mode: In this mode, the pill-sized robot autonomously navigates in the GI tract. Most of the time, the robot utilizes the forward gait with a constant speed. When some predefined events occur, the robot will follow a predefined behavior. We introduce behavior-based robot programming in the next subsection.

6.3.2 Behavior-Based Robot Programming

Robot architecture determines how the robot takes sensor information, processes it, and takes actions accordingly. Robot architecture can be generally categorized as deliberative/hierarchical control, reactive behavior-based architecture, and hybrid systems which combines the former two methods [24]. The deliberative systems are hierarchical in structure with a clearly identifiable subdivision of functionality, where communication and control occur in a predictable and

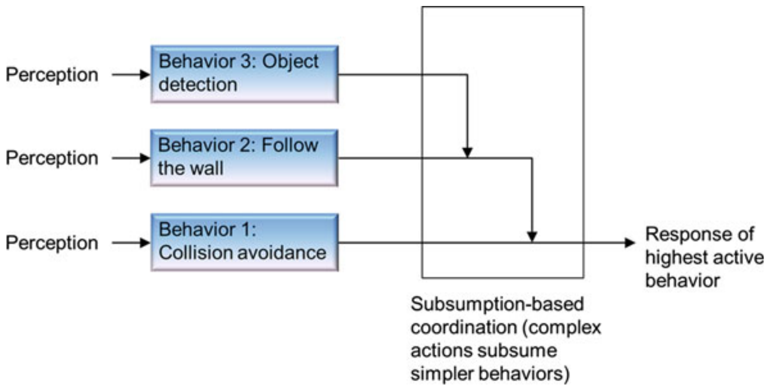

Fig. 6.3 Behavior-based robot programming for pill-sized robot navigation

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 which then are 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 [24]. Due to fast action and its robustness, it has been commonly used in robotics research and practices since its inception in the 1980s. The key aspect in the behavior-based control is how to coordinate behaviors. The popular subsumption architecture uses separated layers to represent individual goals which may happen concurrently and asynchronously. We adopt the behavior-based control in programming the micro-robot in the GI tract, and explain the method next.

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

Behavior 1: 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.

Behavior 2: Following the wall: It is the behavior that the micro-robot follows one side of the wall of the GI tract to navigate. The robot may operate under this behavior most of the time.

Behavior 3: Object detection: It is the behavior that the robot may slow down and take extensive pictures and sensing measurements when it detects inimical tissues. It may also issue an alert signal and send it to a human operator or a doctor for further checkup.

The above behaviors are organized in a subsumption-based coordination scheme, see Fig. 6.3, where the lower level behavior has a higher priority to be

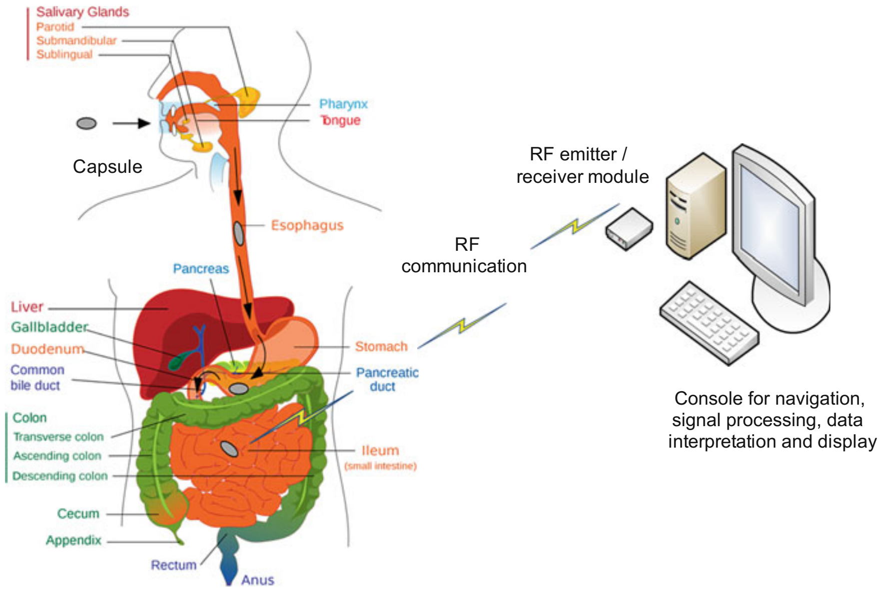

Fig. 6.4 An ingested capsule communicates wirelessly with an external control console

activated. That is, the robot may operate under "follow the wall" behavior when entering the GI tract; as soon as the sensor input indicates an "obstacles" on it 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 distinct between them real time through its sensor input.

6.4 Laboratory Module to Simulate Capsule Robot in GI Tract

The process of an ingested capsule communicating wirelessly with an external control console is shown in Fig. 6.4. The capsule robot is swallowed by the patient and traverses the esophagus, stomach, small intestines, and big intestine. During the robot navigation, the robot captures the information of the GI tract and transmits the data to the external console through the on-board communication module. Prior to the navigation, the external console may get a map of the GI tract and the approximate positions of the regions with potential problems in the tract. In the semi-autonomous mode, the clinician can drive the capsule robot to the desired places that are needed to acquire more detailed information.

To simulate the robot behaviors in the GI tract, we built a biomedical environment in the Webots simulator to imitate the GI tract. In the next, we first introduce the Webots simulator, and then present the robot simulation results.

6.4.1 Webots 3D Robotic Simulator

Webots is a software for fast prototyping and simulation of mobile robots. It has been developed since 1996 and was originally designed by Dr. Olivier Michel at EPFL, the Swiss Federal Institute of Technology in Lausanne, Switzerland, in the lab of Prof. Jean-Daniel Nicoud. Since 1998, Webots is a commercial product and is developed by Cyberbotics Ltd. This software has been used by over 750 universities and research centers worldwide. It offers a rapid prototyping environment, which allows the user to create 3D virtual worlds with physics properties, such as mass, joints, friction coefficients, etc. The user can add simple passive objects or active objects called mobile robots. These robots can have different locomotion schemes (wheeled robots, legged robots, or flying robots). Moreover, they may be equipped with a number of sensor and actuator devices, such as distance sensors, drive wheels, cameras, servos, touch sensors, emitters, receivers, etc. Finally, the user can program each robot individually to exhibit the desired behavior. Webots contains a large number of robot models and controller program examples to help users get started [25].

The graphic user interface (GUI) of Webots is composed of four principal windows: the 3D window that displays and allows to interact with the 3D simulation, the Scene tree which is a hierarchical representation of the current world, the Text editor allows to edit source code, and finally, the Console that displays both compilation and controller outputs, see Fig. 6.5.

A Webots simulation consists of the following components:

- A Webots world file that defines one or more 3D robot and their environment.
- Controller programs for the robots.
- An optional Supervisor.

A world, in Webots, is a 3D description of the properties of robots and of their environment. It contains a description of every object: its position, orientation, geometry, appearance (like color or brightness), physical properties, type of object, etc. Worlds are organized as hierarchical structures where objects can contain other objects (like in VRML97). For example, a robot can contain two wheels, a distance sensor and a servo which itself contains a camera, etc. A world file does not contain the controller code of the robots; it only specifies the name of the controller that is required for each robot. Worlds are saved in wbt files. The wbt files are stored in the worlds subdirectory of each Webots project.

A controller is a computer program that controls a robot specified in a world file. Controllers can be written in any of the programming languages supported by Webots: C, C++, Java, URBI, Python, or MATLAB. When a simulation starts, Webots launches the specified controllers, each as a separate process, and it associates the controller processes with the simulated robots. Note that several robots can use the same controller code; however, a distinct process will be launched for each robot. Some programming languages need to be compiled (C and C++), other languages need to be interpreted (URBI, Python and MATLAB), and some need to be

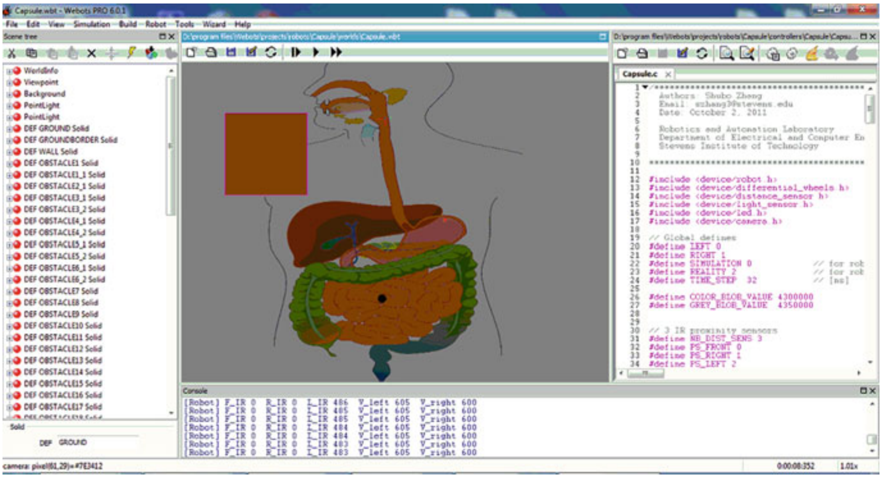

Fig. 6.5 Webots GUI composed of the scene tree (*left*), a display window (*top middle*), a text editor (*top right*), and the console window (*bottom*)

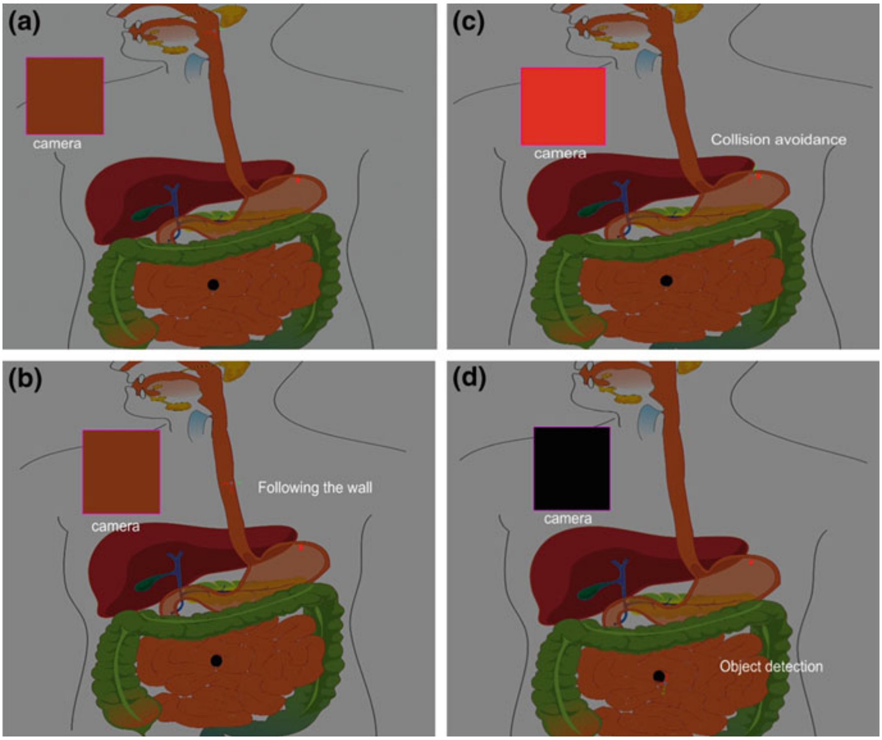

Fig. 6.6 The robot navigating in the GI tract: **a** The robot enters the GI tract; **b** Follow the wall behavior; **c** Collision avoidance behavior; **d** Object detection behavior

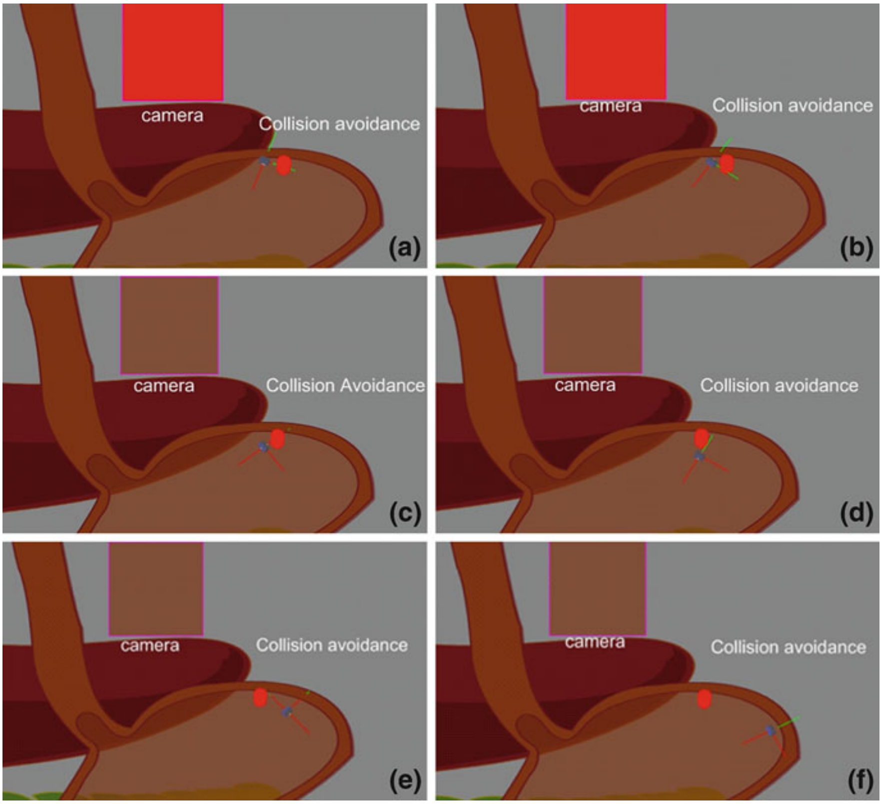

Fig. 6.7 Snapshots of the collision avoidance behavior: **a** The front camera detects the obstacle; **b** The robot starts to go around the obstacle; **c**–**e** The robot avoids the obstacle; **f** The robot resumes the follow the wall behavior

both compiled and interpreted (Java). For example, C and C++ controllers are compiled to platform-dependent binary executables (for example, .exe under Windows). URBI, Python, and MATLAB controllers are interpreted by the corresponding run-time systems (which must be installed). Java controllers need to be compiled to byte code (class files or jar) and then interpreted by a Java Virtual Machine. The source files and binary files of each controller are stored together in a controller directory. A controller directory is placed in the controllers subdirectory of each Webots project.

The Supervisor is a privileged type of Robot that can execute operations that can normally only be carried out by a human operator and not by a real robot. The Supervisor is normally associated with a controller program that can also be written in any of the above-mentioned programming languages. However, in contrast with a regular Robot controller, the Supervisor controller will have access to privileged operations. The privileged operation includes simulation control, for example, moving the robots to a random position, making a video capture of the simulation.

6.4.2 Webots Simulation of Capsule Robot in GI Tract

We have programmed the pill-sized capsule robot according to the behavior-based navigation and control design described in Sect. 6.3. We simulate a scenario of the robot passing through the GI tract under the pre-programmed behaviors, as shown in Fig. 6.6, where the robot enters the GI tract in Fig. 6.6a, and then navigate in Fig. 6.6b–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 anytime. The rectangular color block in each figure represents the real-time camera output during the navigation of the robot in the GI tract. The robot is equipped with proximity sensors (left and right) to detect relative positions with the walls, and a front camera to detect objects.

To have a close view of the behavior, we show the snapshots of the collision avoidance behavior in Fig. 6.7, where the onboard camera in front of the robot detects an obstacle in Fig. 6.7a, and the robot starts to go around it in the consequent subfigures b, c, d, and e. After it exits the collision avoidance behavior, the "following the wall" behavior is resumed to continue navigation.

6.5 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 chapter, we present a conceptual design of a capsule robot navigating in the human's GI tract. Behavior-based programming was introduced to control the robot navigation in the human's body. A laboratory module was then developed to demonstrate the behaviors of the robot on the platform of the Webots simulator.

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